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TR 76-6

TECHNICAL REPORT NO. 76-6

SHALLOW BOREHOLE CONVECTION NOISE STUDY

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TELEDYNE GEOTECH

TECHNICAL REPORT NO. 76-6

SHALLOW BOREHOLE CONVECTION NOISE STUDY

by

John R. Sherwin
and
John C. Cook

Sponsored by

Advanced Research Projects Agency
ARPA Order Nos. 2551 and 2879

TELEDYNE GEOTECH
3401 Shiloh Road
Garland, Texas

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The purpose of this study was to determine the cause or causes of extraneous noise on the horizontal channels of the Borehole Seismometer System, Model 36000, and to develop methods of reducing or eliminating this noise. Similar noise had been observed on other borehole seismographs in the past and was later found to have been caused by the action of convection cells in the air within the sealed borehole.

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cont.

20. ABSTRACT, Continued

The plan of the tests was, first, to determine what input mechanism caused the characteristic noise (horizontal channel outputs with little or no vertical response) and, secondly, to investigate as many causes as possible of such an input, whether they be external to the instrument or due to forces acting directly on it in its borehole environment. Primary emphasis was placed on detection and identification of air convection activity by pressure and thermal sensors, and on repeatable generation of artificial convection activity to demonstrate effectiveness of various methods to reduce their effects.

Theory showed that instrument tilt, whatever the source, was the direct cause of the noise which affects horizontal channels only. The horizontal seismometer was found to be about 200 times more sensitive to tilts than to displacements, indicating that this type instrument must be adequately protected from tilting to prevent spurious outputs. Testing was done from March through May 1976 at Garland, Texas. The first tests confirmed reports by others that wind pressure loading of the earth results in tilting at longer periods. Another test showed that much of the noise termed "convection noise" at Garland was actually due to movements of heavy trucks in the area and theoretical calculations confirmed the phenomena. Another test showed that the pressure sensitivity of the Model 36000 was high enough to result in tilt noise if the borehole was unsealed, subjecting the instrument to normal atmospheric pressure disturbances. However, the system was not found to be sensitive enough to react directly to the low-level pressure disturbances normally detected in sealed boreholes. The KS package was found to be most sensitive to temperature changes in its holelock and/or base and several tests were performed to determine the reaction of the instrument to artificially generated convection activity below the holelock. The microbarograph and thermistor detected convections and an accompanying reaction was noted on the KS horizontals. However, spectral analysis indicated that the KS noise was not linearily related to either pressure or temperature (at the point measured).

The overall conclusions of this study are (1) much of the noise at Garland thought to be convection-related is actually due to other sources; (2) natural convections caused by inverse thermal gradients in sealed boreholes are difficult to detect using present instrumentation due to their random nature; and (3) convection activity near the KS holelock is likely to induce tilt noise on the KS horizontal traces by changing the temperature of the support components. It is recommended that insulation be added below and inside the holelock in order to minimize thermal effects from convections or any other source.

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CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS, Continued

ILLUSTRATIONS, Continued

ILLUSTRATIONS, Continued

TABLES

SHALLOW BOREHOLE CONVECTION NOISE STUDY

1. INTRODUCTION

Early work with long-period seismometers under the Long-Range Seismic Measurements (LRSM) program which began in 1960 showed that these instruments became very noisy if subjected to temperature changes. Therefore, installation techniques were developed over several years to protect these instruments from the effects of temperature changes. The first procedure was to protect the instrument from external temperature changes by fully insulating inside and outside surfaces of the tank vaults. Tests then showed inverse thermal gradients (warmer at the bottom) occurred even in sealed and insulated vaults which caused air motion due to convection and, in turn, caused thermal noise in the instrument. A technique found helpful in this case has been to place a heat source inside the tank lid to stratify the air inside the sealed vault in order to prevent the movement of air due to convection. These and other techniques have continued to be used for surface installations.

During the winter of 1970-71, studies were made at the Alaskan Long-Period Array (ALPA) to determine the cause of high-level noise on the triaxial long-period instruments which were installed in 15 m deep cased boreholes. This noise was three to four times larger than normal seismic background and occurred only during subfreezing weather. The field tests, reported by Teledyne Geotech (1971), confirmed that the noise was due to relatively high-level pressure changes within the sealed borehole and that these pressure changes occurred when the top of the borehole was cooled. It was then postulated that the pressure changes were caused by moving convection cells produced when the air column was in the thermally unstable condition of being warmer at the bottom than at the top. This problem was finally solved by filling the upper 6 m of the borehole with loose, granular insulation.

During the development of the Kirkpatrick-Starkey (KS) seismometer modules in 1972, a similar problem was noted. Relatively larger noise signals were observed on the data traces from the experimental modules which were sealed from atmospheric pressure disturbances. Because the KS modules contain a small heat source near the bottom of their sealed cases, it was again postulated that convection cell activity was the cause of the noise. To verify this theory, the modules were modified to maintain a vacuum of 1 torr (1 mm Hg) or better. When the evacuated modules were placed in operation, the noise was not seen. With this evidence, the KS module design was changed to incorporate evacuation of all modules as part of the manufacturing process.

Finally, testing of the Model 36000 Borehole Seismometer System began in Garland in 1973 as reported by Sherwin and Kraus (1973) and was extended to deep borehole operation at Pinedale, Wyoming, in 1974, as reported by Douze and Sherwin (1975). These operations identified and eliminated some noise sources on the Model 36000 data traces. Insulation was added inside the instrument and also wrapped around the outside of the cylindrical package which reduced the settling time and eliminated much spiking normally attributed to thermal noise in the mechanical parts. The analog electronic circuits were also improved to eliminate noise. With these and other improvements, the Model 36000 was able to achieve operating magnifications equal to or better than any other long-period installation in the world.

Nevertheless, there remain to date occasional occurrences of low-level noise on the horizontal KS traces. Sherwin and Kraus (1973) reported tests in which two horizontal instruments, oriented in the same direction, produced very coherent noise data in the Garland boreholes and in a borehole near McKinney, Texas, suggesting a common source. Similar conclusions were drawn from data obtained with the instrument submerged in water at Garland and Pinedale reported by Douze and Sherwin (1975). Past experience with the effects of convection activity therefore quite naturally led to the conclusion that any otherwise unexplained noise which affects KS horizontal data traces was due to convection. Hence the term "convection" noise was adapted without conclusive evidence that convection activity was the cause.

The purpose of this study was twofold: first, to discover the cause of "convection" noise on KS horizontals by measurement of the disturbance using an independent instrument and second, to determine methods of eliminating or reducing these disturbances either by controlling them directly or by protecting the Model 36000 from them. This report describes the work performed during the period from March through mid-June 1976, under the Special Studies portion (task 4.2) of the Special Data Collection System (SDCS), Project T/4703. The report is submitted in accordance with Sequence No. A007 of the Contract Data Requirements List as amended under Modification P00005, 2 January 1975. This research was supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by AFTAC/VSC, Alexandria, Virginia 22314, under Contract F08606-74-C-0013

2. DATA COLLECTION

All data for this program were collected at Geotech's test borehole in Garland, Texas. The site coordinates are 32°52'30"N and 97°37'40"W and the site designator assigned is GL-TX. The borehole is approximately 100 m (328 ft) deep and is fully cased with 7-5/8 in. API steel casing. The hole is filled with water to the 75 m (246 ft) level, and the KS operating depth for all tests was 61 m (200 ft). A sketch of the test area is shown in figure 1.

2.1 TEST PLAN

The overall plan of this program was divided into the following tasks:

a. Review of prior related testing by Geotech and USGS;

b. Determine whether convections could cause noise by artifically exciting them;

c. Determine how the convection cells cause noise on KS data traces;

d. Develop techniques to minimize or eliminate the effects of convection activity.

A test plan was then developed to accomplish these goals. It was expected that changes would be required during the course of the program as the various tests provided better insight into the problem. While there were some changes, most of the tests were performed according to the plan which included the following items:

a. Set up necessary support equipment - recorders, filters, amplifiers, etc;

b. Modify holelock and/or Model 36000 for heaters below holelock and near top of Model 36000 package;

c. Install holelock above water level and determine orientation;

d. Install Model 36000, S/N 004, in standard configuration;

e. Install microbarograph (MKB) to sense borehole pressure changes; seal borehole;

f. Determine transfer function and sensitivity of Model 36000 to pressure changes;

g. Induce convections at top of borehole and note KS reaction, if any;

h. Induce convections below holelock and note KS reaction; repeat;

i. Induce convections near top of KS and note KS reaction; repeat;

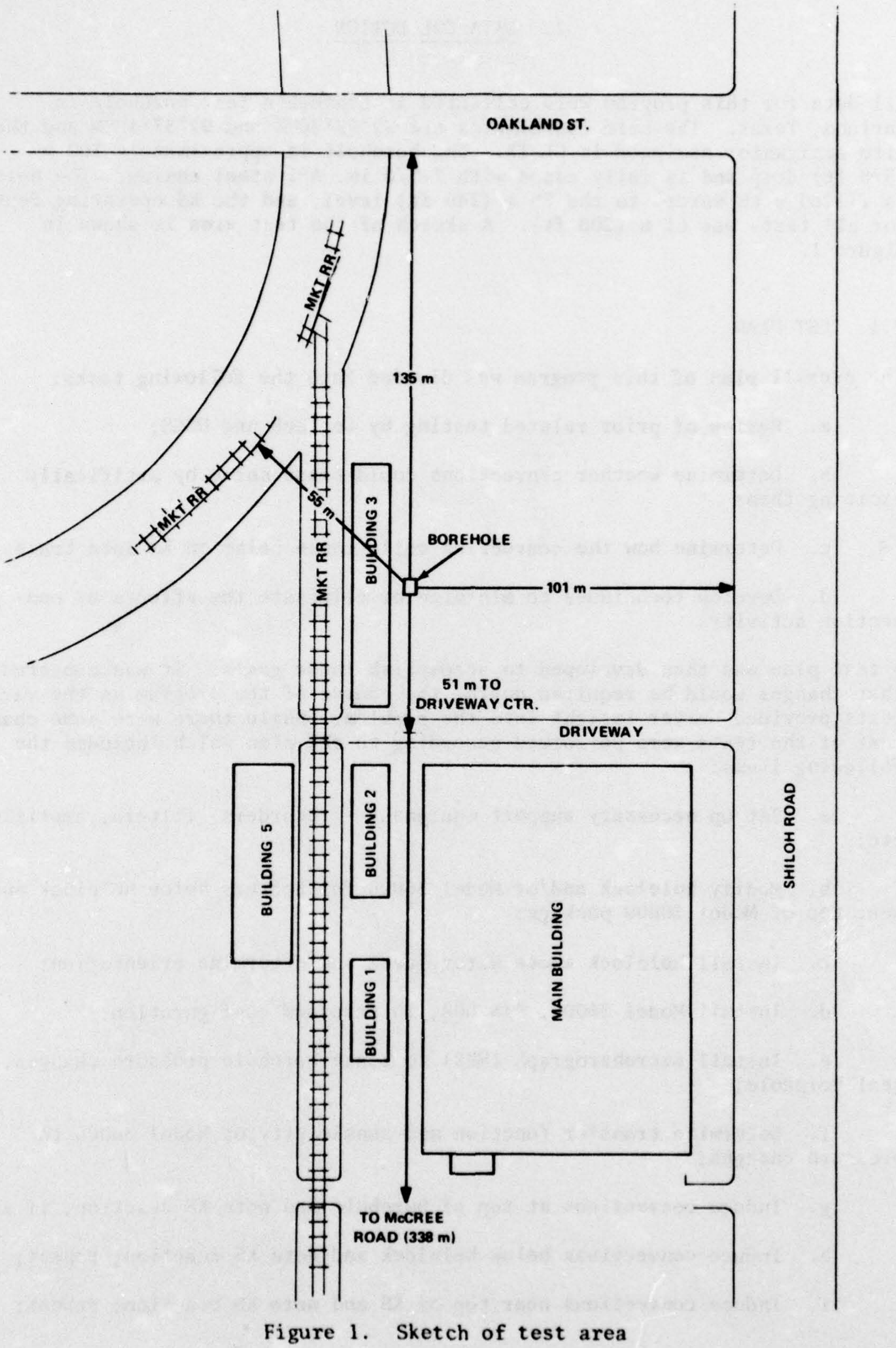

Figure 1. Sketch of test area

G 8956

j. Move holelock to submerge in water and reinstall KS;

k. Induce convections at most sensitive point to establish control data base;

l. Test various hardware modifications to determine effectiveness in reducing KS response to activity;

m. Test various methods of controlling activity directly such as insulation;

n. Terminate testing and write report.

2.2 EQUIPMENT

A simplified block diagram of the equipment used for this program is shown in figure 2. The seismic system includes a standard Model 36000, S/N 004, short-and long-period filters as developed for the U.S. Geological Survey Program and a standard Signal Control Center, Amplifier Module (SCC) for post-amplification of the filtered data. The environmental equipment includes a standard microbarograph (used to sense external pressure and upper borehole pressure), a special microbarograph small enough to install inside the 7-inch diameter casing, thermistors for sensing thermal gradients and changes, and various heaters to excite convections. Visual data were recorded on three Helicorders, an 8-channel Develocorder, and a strip-chart recorder (for temperature data). Data were also recorded on FM magnetic tape during the first month of operation and thereafter on four channels of Geotech's Raytheon Computer system.

Figure 3 shows the response of the two seismograph systems. The study was based primarily on the analysis of long-period data. Short-period data were recorded on film only and were useful in analyzing LP data to determine presence of seismic signals, high frequency noise, etc. Short-period data were also used to verify that the noise in question was not due to non-linear response of the LP filters to large out-of-passband SP signals and noise. The microbarograph response curve shown is correct for the borehole microbarograph, but the standard unit begins to roll off faster at the longer periods. Temperature data were recorded on film and tape using a 200-second high-pass filter (to eliminate long-term dc signals) and a 3-second low-pass filter until 16 May when the filter corner was changed to 18 seconds. The strip chart recorder recorded data from dc to 18 seconds. Finally, the long-period traces were further filtered for film only using 30-second 18 dB/octave low-pass filters to enhance the longer period noise on these traces.

The Model 36000 was modified slightly for the tests. Figure 4 is a sketch of the lower portion of the Model 36000 as installed in the borehole showing the position of heaters 1 and 2 and the 35 cm long gradiometer. (The insulating foam plug with the steel sleeve by which it is attached to the holelock, was added midway during the tests.) In addition, a resistive heater (3) was installed to heat the air near the stabilizer fingers on the top of the instrument. A multiconductor cable was used to connect these components to the surface systems.

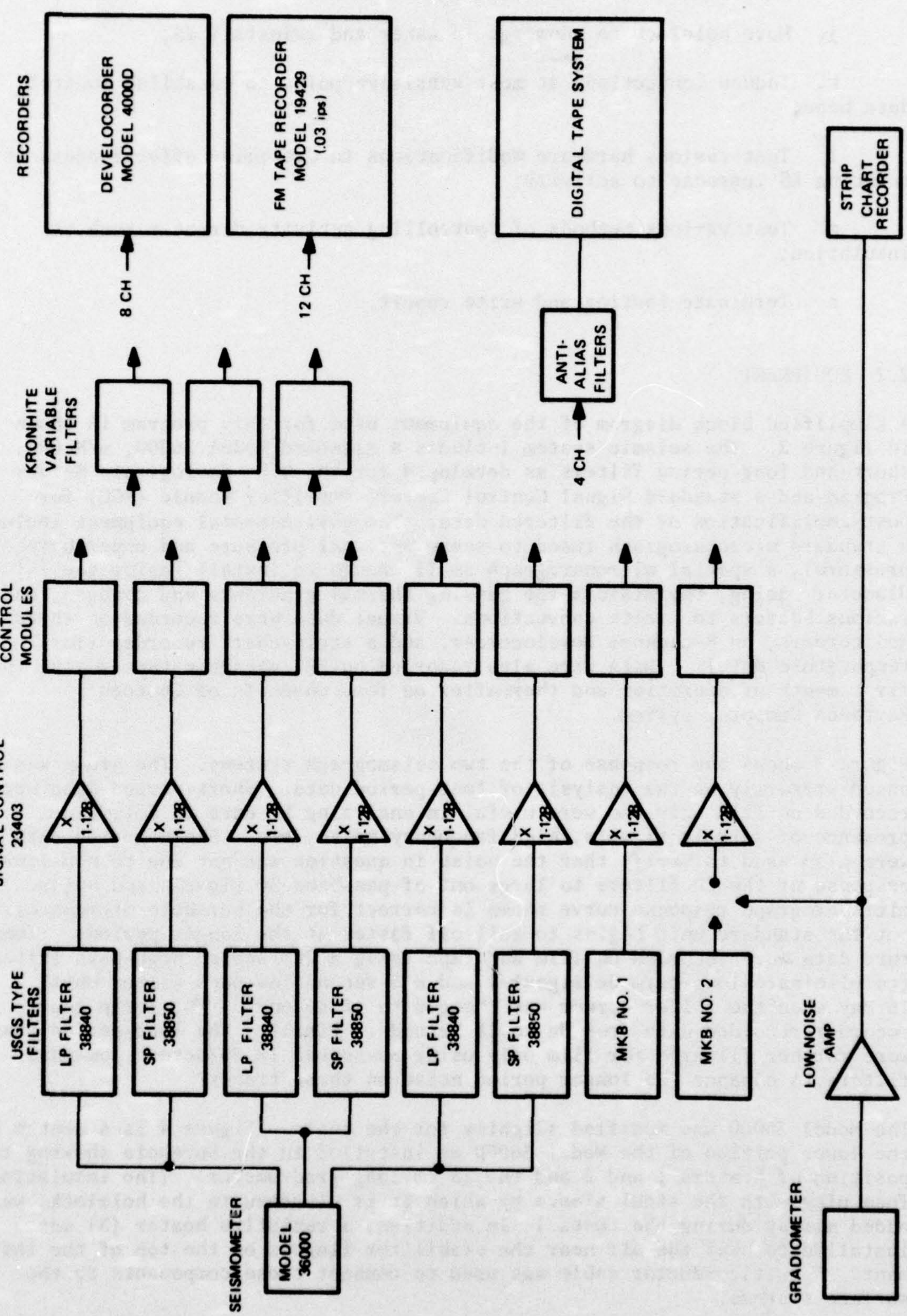

Figure 2. System block diagram

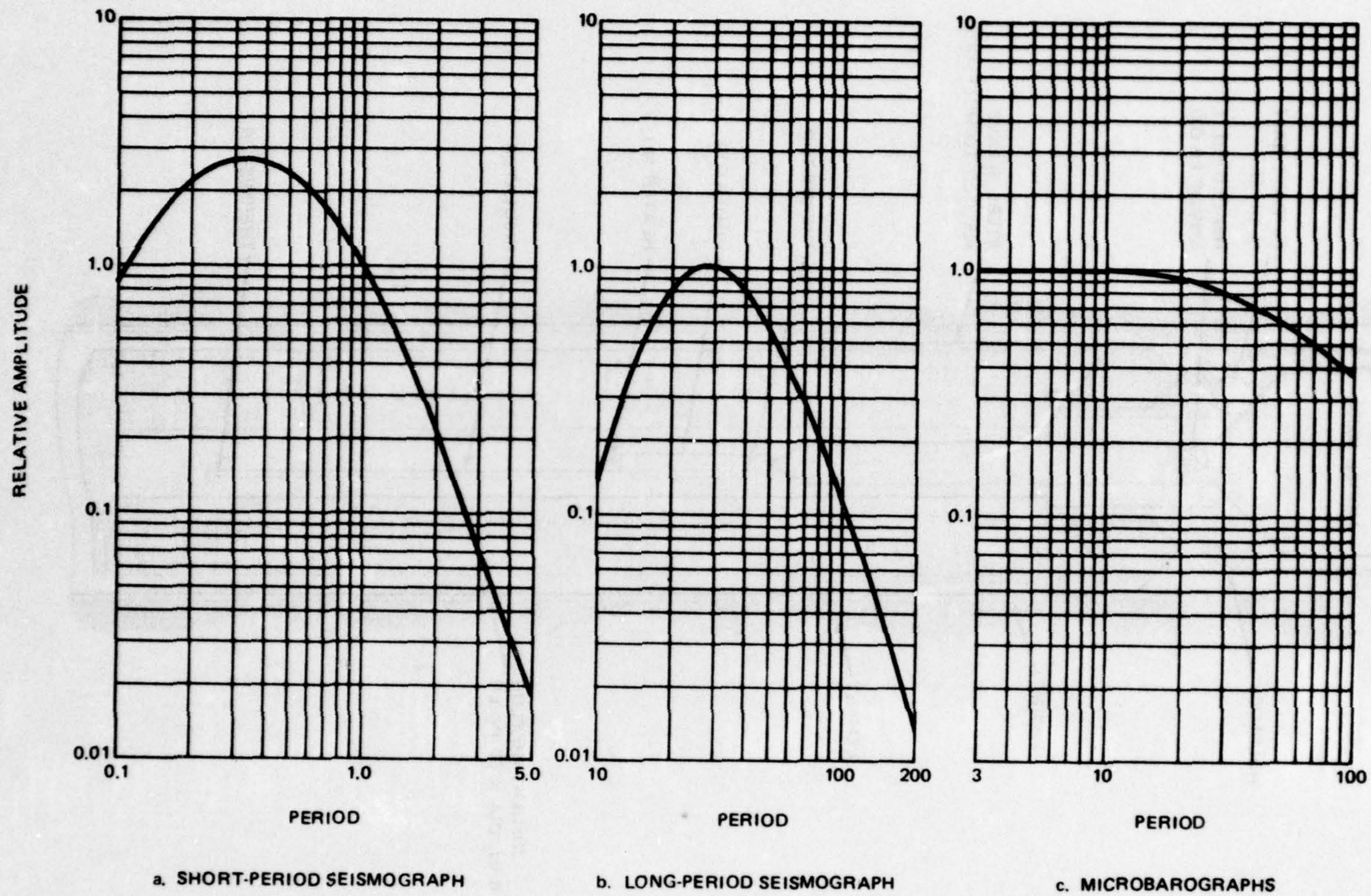

Figure 3. Response of various systems during tests

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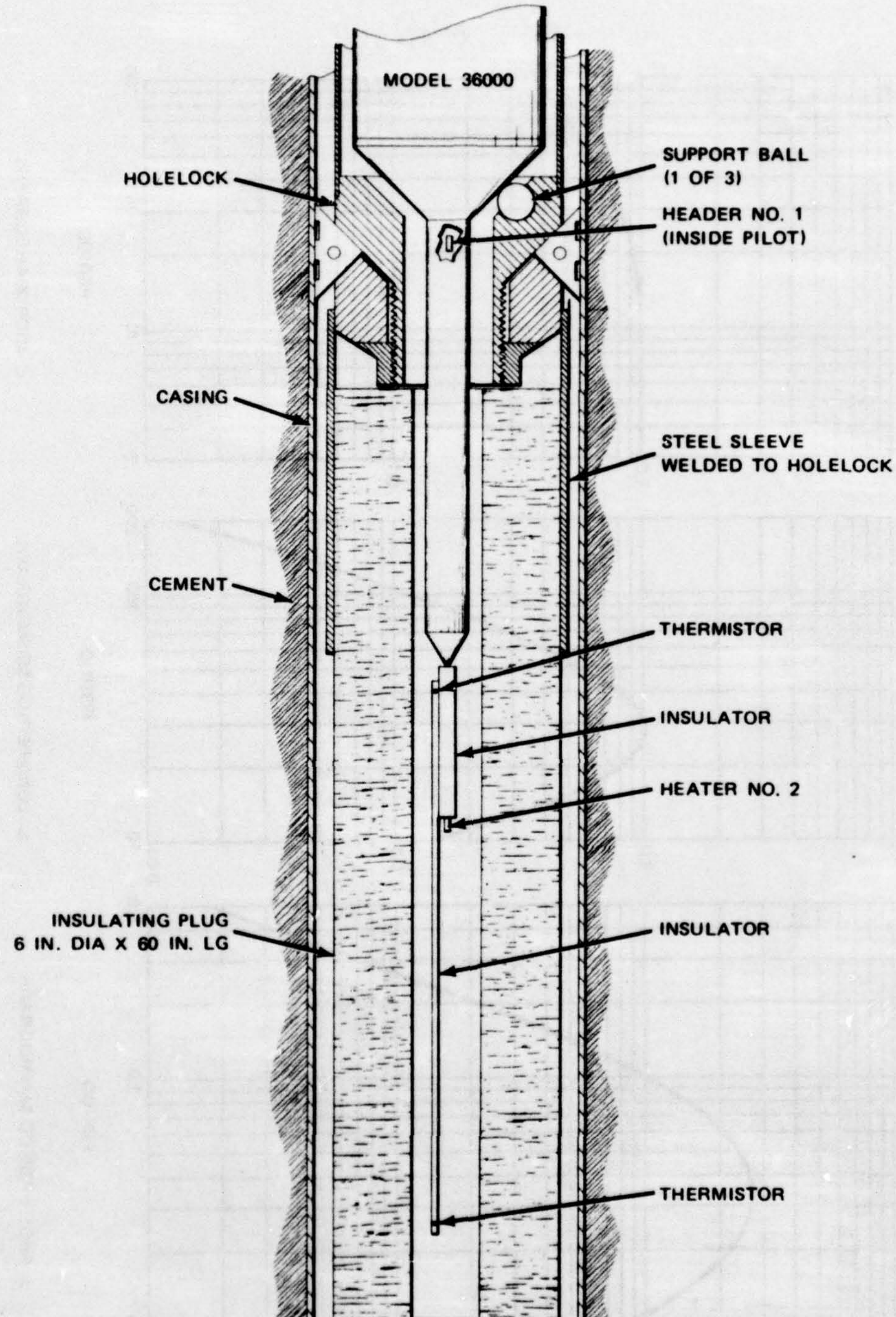


Figure 4. Sketch showing Model 36000 resting on holelock with other items used during tests (see text)

G 8959

2.3 OPERATIONS

The operational portion of this program began with the installation of the KS seismometer on 2 March 1976. Most of the testing was done during the two month period from April to June; operation of the system was terminated on 15 June. During operation, system and operational changes were made as expected as test results indicated the need for more emphasis on a particular aspect of this problem. As an example, tests indicated that the KS was most sensitive to heat near the holelock rather than near the stabilizer as originally expected. As a result, several tests in the test plan relating to upper package restraining methods were not done. In addition, planned tests with the KS under water were not done due to time and budgetary constraints. Various tests in air which were necessary to successfully demonstrate the existence of convection activity and the ability to control it required more time than anticipated - a not uncommon problem in any long-period instrumentation study. Nevertheless, the findings of this study are applicable to any operating environment of the KS system - whether in air or in water.

3. TILT RESPONSE OF THE HORIZONTAL SEISMOMETER

The "convection" noise problem has always involved the horizontal channels of the Model 36000 system; little or no noise has been noted on the vertical channels. For example, the operation during this program allowed magnifications of 100,000 on the vertical (LPZ) channel and one-half that level on the horizontal (LPN and LPE) channels. Since the vertical seismometer is relatively insensitive to small tilts, actual tilting of the package is thought to be the cause of the noise seen on horizontal channels. In this section, the theoretical tilt response of the horizontals will be discussed and some potential causes will be enumerated.

3.1 THEORY

The horizontal pendulum seismometer responds to the component of gravity caused by tilt of its base. Rodgers (1968) discusses this response and shows the relationship between the tilt response, $A_{t(\omega)}$, and the displacement response, $A_{d(\omega)}$, as

$$A_{t(\omega)} = \frac{g}{\omega^2} A_{d(\omega)} \qquad (1)$$

In figure 5, the displacement response of the horizontal KS seismograph is plotted and normalized to a 100K magnification at 25-seconds - an operating level quite easily achieved with this instrument at quiet locations. In addition, the tilt response computed from equation (1) is shown in the figure, in terms of meters out per radian input. Note that the tilt response results in an emphasis on the longer periods, with a peak level of about 35,000K magnification at 50-60 seconds.

To illustrate the sensitivity of the horizontal seismograph to tilt, consider the following numerical example. Suppose that a 5 mm pulse at 50 seconds is measured on a 50K horizontal channel at GL-TX. In terms of horizontal displacement, the equivalent input is calculated to be 172 nm. If this same displacement acts horizontally to tilt the 3 m long KS package (assuming that one end is fixed), a tilt of 5.73×10^{-8} radian is produced. From figure 5, the output trace deflection would be 1 meter! Obviously, the effects seen on KS horizontal records are not this large, but the example does illustrate what can happen. Thus, it can be seen that a horizontal instrument must be installed so as to protect it from spurious tilt inputs if the much smaller displacements are to be detected.

3.2 SOME POTENTIAL CAUSES OF TILT IN THE KS INSTRUMENT

Tilts in any horizontal seismometer can be broadly classified as (1) those resulting from external forces on the earth and (2) those resulting from forces acting directly on the instrument itself. In the first case, tilts can arise from the forces of winds moving across the installation or from cultural activity near it. Such tilts have been treated by many authors and are reasonably predictable by theories of deformation of the earth. In the second case, tilts can result from any phenomenon which causes mechanical stress in the package, such as temperature, pressure or stress in the supports or immediate environment of the installation. Such forces are difficult to predict theoretically, a fact confirmed by numerous tests on the Symmetrical Triaxial Transducer, Model 31300, which were made as a result of the Alaskan noise field study (Teledyne Geotech 1971) and reported by Teledyne Geotech (1972). Tests conducted under this program again demonstrated the difficulties involved in theoretically predicting expected output from the KS instrument. In the following paragraphs, various tests are discussed which were performed to better understand these sources of tilt.

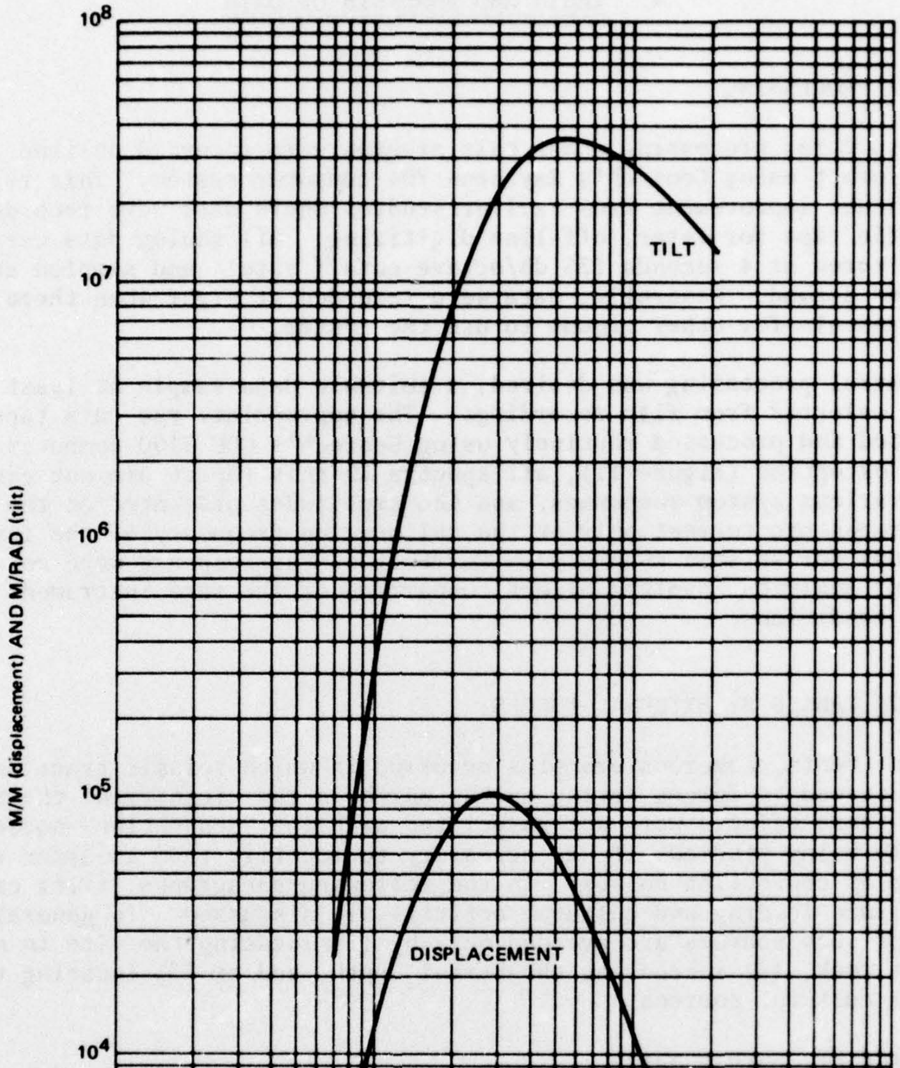


Figure 5. Response of horizontal KS seismographs to displacement and tilt

G 8960

4. TESTS AND ANALYSIS OF DATA

4.1 DATA PROCESSING

Data for spectral processing under this program were recorded on-line in digital format using Geotech's Raytheon 704 computer system. This represents a significant improvement from earlier studies where data were recorded on FM magnetic tape for later, off-line digitizing. All analog data were anti-alias filtered at 4 seconds (36 dB/octave cutoff rate) and sampled at 1.0 sample per second. Generally, data were recorded at night when there were no requirements for other groups to use the system.

When spectral processing was desired, a suitable data sample at least 1.5 hours long was selected from film recordings. The appropriate raw data tapes were reformatted and processed routinely using Geotech's CDC 3100 computer system. With one exception (figure 11), all spectra in this report are not corrected for the various system responses. and the amplitudes presented on the ordinates of the graphs are correct only at the calibration frequency of the instrument (25 seconds for seismic channels). Corrections for response were not necessary since most analyses involved direct comparison of the same instrument under variable conditions.

4.2 TILTS CAUSED BY EXTERNAL FORCES

During the tests, numerous examples occurred in which seismic trace deflections could be traced to forces acting on the earth in the vicinity of the boreholes. Although these effects were not associated with the "convection" noise sources which were being studied, it was necessary to identify them in order to eliminate them as convection noises. In the following paragraphs, tilts caused by wind pressure loading and cultural activity are discussed. In general, the effects of such sources are avoided only by (1) locating the site in more competent rock, (2) increasing the burial depth, and/or (3) locating the site away from cultural sources.

4.2.1 Wind Pressure Loading

The generation of earth noise due to atmospheric pressure variations is discussed at length by, among others, Sorrels (1971), Sorrells and Douze (1974), and Douze (1975). A thorough discussion of such noise sources is beyond the scope of this report and the reader is referred to the literature. However, there were examples of such noise during these tests. Figure 6 shows the external microbarograph responding to pressure fluctuation of about 60 μbar at 120 seconds (corrected for response) at 0725Z. The horizontal channels are responding to this external pressure at corrected equivalent input levels of 5.1 and 2.9 nm on the LPN and LPR traces, respectively. These levels are very near those predicted by Sorrells (1971) using the 60 m installation depth and the geology of the area.

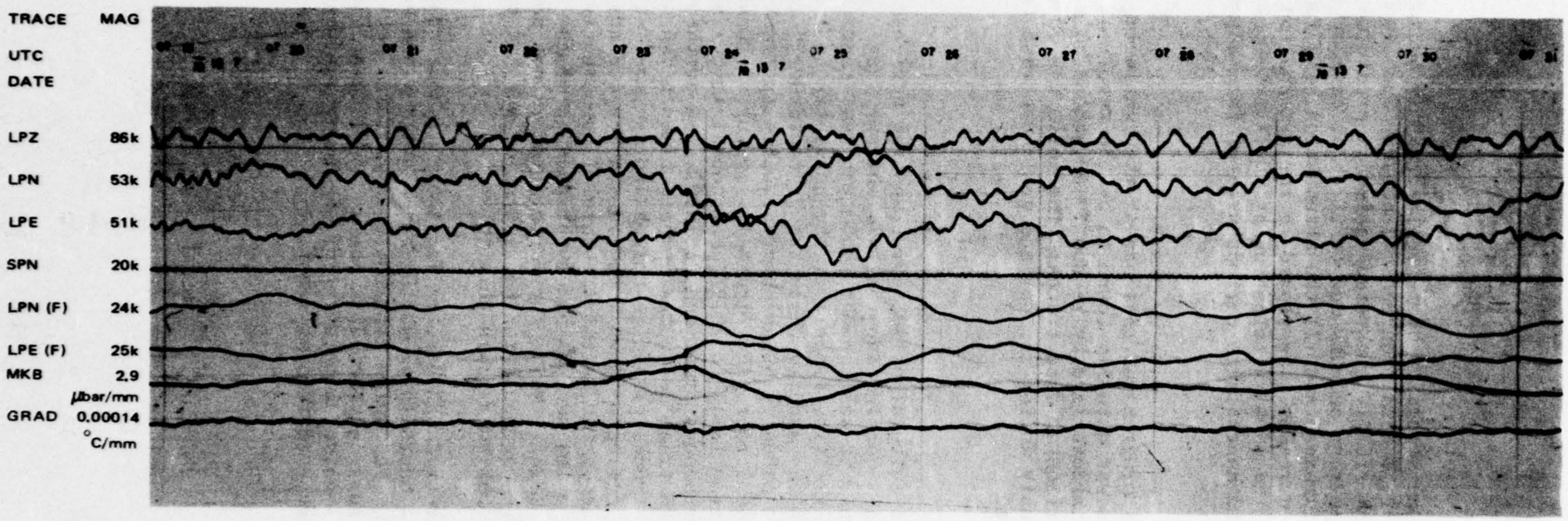


Figure 6. Reproduction of a 16 mm film recorded at Garland, Texas, on 16 May 1976, showing tilts on LP horizontal traces due to wind-pressure loading associated with a cold front passage

Tilt noise of this type can generally be recognized easily because it is usually much longer in period than "convection" noise. Such emphasis on the longer periods for atmospherically generated noise is predicted by the theory for two reasons: (1) apparent outputs due to tilt increase by the square of the period of the disturbance and (2) the attenuation as a function of depth decreases as the period increases. In regard to the attenuation with depth the theory predicts that the 60 m installation at GL-TX provides little, if any, protection from disturbances with periods greater than about 40 seconds.

4.2.2 Cultural Activity

One discovery during this program was that one of the continuing noise sources attributed to convections was actually found to be the result of local cultural noise. This noise was characterized by random 30-40 second pulses at about 5 mm primarily on the horizontal data traces. The noise was generally observed to occur almost continuously during the day and would decrease to only an occasional pulse at night.

4.2.2.1 Tests Performed

The first indication of a cultural noise source was the decrease in such activity during the weekend period. Considering that similar but larger pulses were produced by passing trains, it was thought that this semi-continuous diurnal noise was caused by road traffic, especially the heavy trucks frequenting this area. A short experiment was made in which the Develocorder "time" slashes were placed on the record manually by an observer watching trucks pass on Shiloh Road and on Oakland Street (see figure 1). Figure 7 shows a sample of the results. Note that from 1814Z to 1817Z, horizontal traces are relatively quiet. At 1817:40Z a northbound truck and at 1819Z, two northbound trucks passed on Shiloh. The LPN trace deflected up both times a few seconds later. At 1823Z, two southbound trucks passed on Shiloh and two more at 1824Z. In this case, the LPN trace deflected down both times a few seconds later. For each of the four occurrences, the vertical channel is apparently responding by deflecting down, then up a few seconds after the passage of the truck. This is especially noticeable at 1824Z. While the correlation is not perfect (there is similar traffic at a large warehouse to the west which was not visible to the observer), it is high enough to explain this noise.

Figure 8 shows the uncorrected LPN spectra for two, 2-hour samples - one during the day and one 12 hours later during the night. Winds were light to calm during both periods. The noise attributed to cultural activity causes a significant increase in noise on the 1755Z sample, particularly at the long periods. Because of this noise, a majority of the important tests discussed later in this report were performed at night.

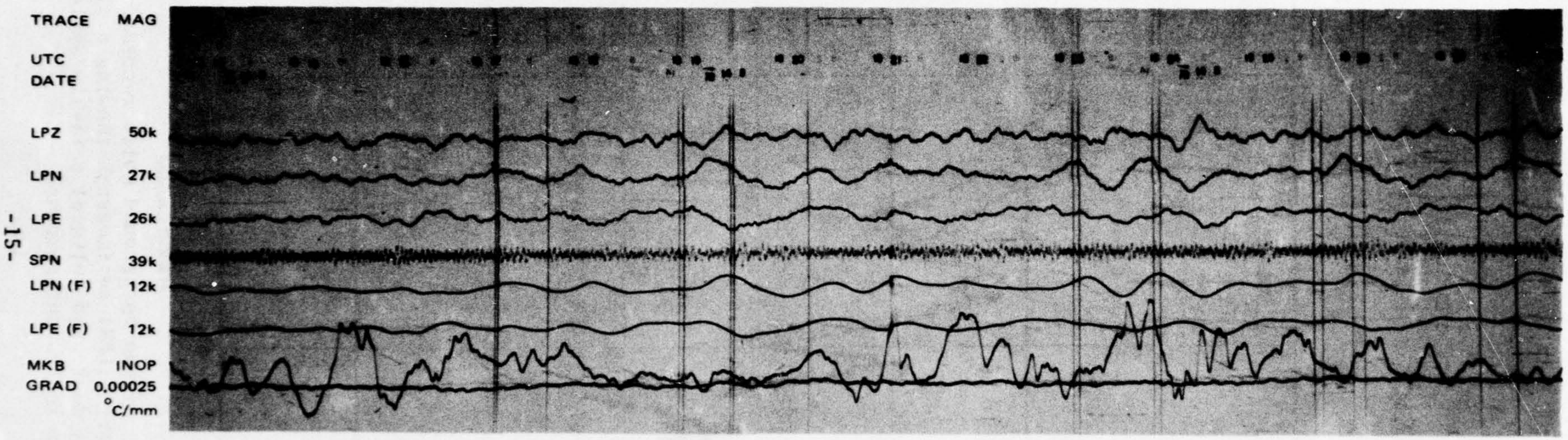


Figure 7. Reproduction of a 16 mm film recorded at Garland, Texas, on 23 May 1976, showing tilts on LP horizontals caused by passage of heavy trucks at a minimum distance of 100 m. Time slashes were made manually as vehicles made closest approach

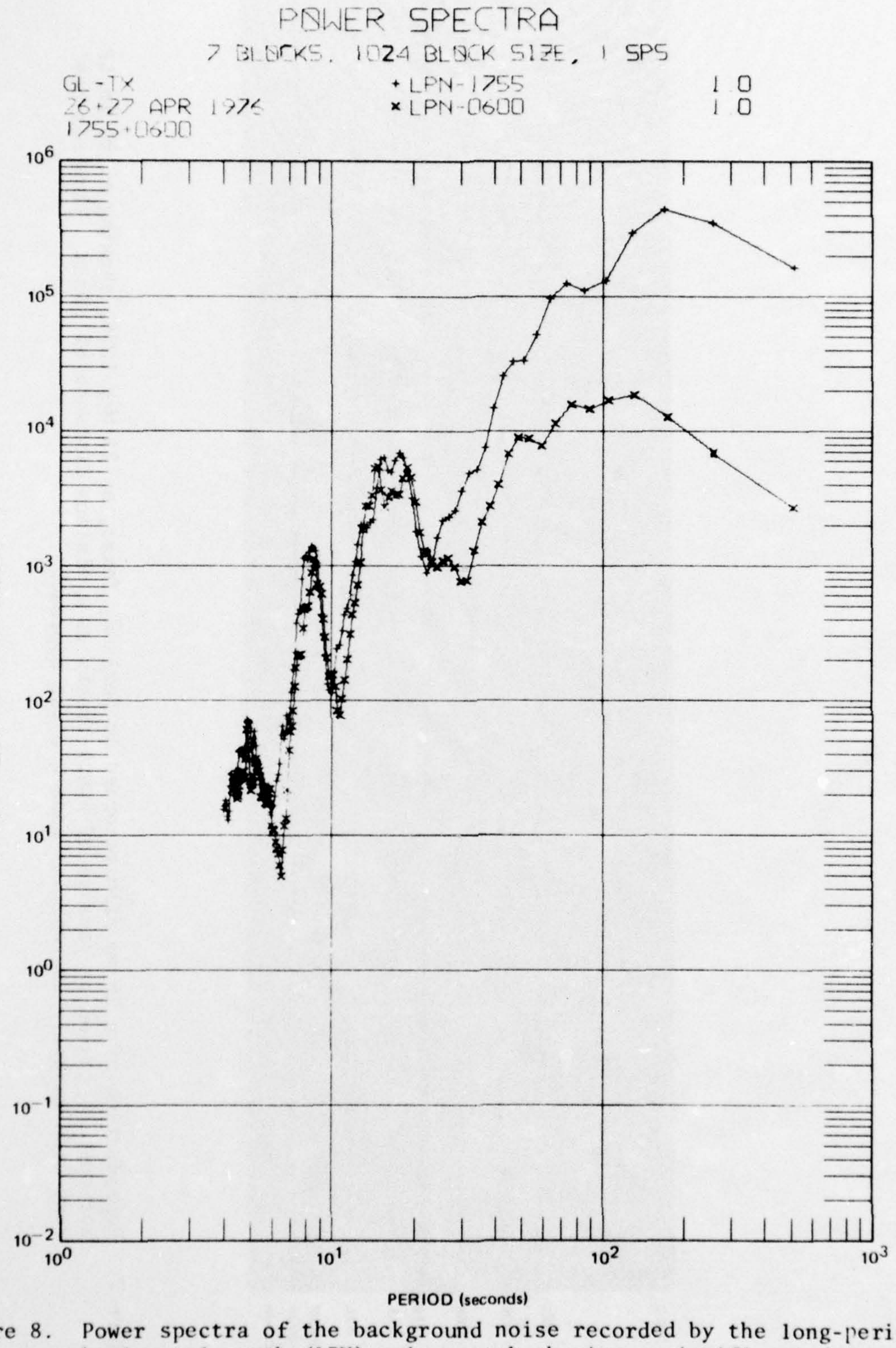


Figure 8. Power spectra of the background noise recorded by the long-period horizontal north (LPN) seismograph showing a significant decrease in level with decreased cultural activity during the night. Not corrected for instrument response

G 8961

4.2.2.2 Steady-State Distortion of the Earth

Order-of-magnitude calculations were performed to see whether the peak of the forcing function produced by a passing truck should be capable of generating the observed "event." The KS seismograph at z = 60 m deep in the well is considered to be immersed in a uniform half-space of elastic constants, E, μ and σ. This is approximately true since the soil here is only 4 m thick (from borings) and the Austin chalk below it is about 240 m thick. The truck at radial distance r, and horizontal distance x, applies chiefly a vertical force F_z, by its weight of 7 metric tons (empty) to 36 metric tons (loaded). Accelerations and decelerations from braking and turning rarely exceed 0.1 g, but these horizontal forces also distort the earth.

Boussinesq's equations are properly used for the quasi-steady-state forcing function in the "near field" of the truck. Landau and Lifschitz (1959) give these in a convenient form. For the three components of ground displacement μ they give:

$$u_x = \frac{1+\sigma}{2\pi E}\left\{\left[\frac{xz}{r^3} - \frac{(1-2\sigma)x}{r(r+z)}\right]F_z + \frac{2(1-\sigma)r+z}{r(r+z)}F_z + \frac{[2r(\sigma r+z)+z^2]x}{r^3(r+z)^2}(xF_x+yF_y)\right\}, \tag{2}$$

$$u_y = \frac{1+\sigma}{2\pi E}\left\{\left[\frac{yz}{r^3} - \frac{(1-2\sigma)y}{r(r+z)}\right]F_z + \frac{2(1-\sigma)r+z}{r(r+z)}F_y + \frac{[2r(\sigma r+z)+z^2]y}{r^3(r+z)^2}(xF_x+yF_y)\right\}, \tag{3}$$

$$u_z = \frac{1+\sigma}{2\pi E}\left\{\left[\frac{2(1-\sigma)}{r} + \frac{z^2}{r^3}\right]F_z + \left[\frac{1-2\sigma}{r(r+z)} + \frac{z}{r^3}\right](xF_z+yF_y)\right\} \tag{4}$$

The forms of u_x and u_y are identical, so only one needs to be calculated. Furthermore, only the terms of the equations containing vertical force (Fz) need be considered here because surface loads moving in a straight path at constant speed produce vertical forces only. With this simplification, the tilt τ can be obtained by differentiating the formula for u_x:

$$\tau_x = \frac{\partial u_x}{\partial z} = \frac{1+\sigma}{2\pi E}\left[\frac{x}{r^3}\left(2-2\sigma-\frac{3z}{r^2}\right)\right]F_z \tag{5}$$

An expression of the identical form would give τ_y, the tilt in the y (east-west) direction.

4.2.2.3 Predictions of Displacements from Theory

The elastic constants of the Austin chalk have been determined by local seismic velocity measurements (Cook, 1976; White and Sengbush, 1953):

$$V_p = 3000 \text{ m/sec},\ V_s = 1120 \text{ m/sec},\ \rho = 2.5 \frac{\text{gm}}{\text{cm}^3}$$

From these values, the elastic constants (Birch, 1966) are:

$$\sigma = 1/2\ [(V_p/V_s)^2-2]/[(V_p/V_s)^2-1] = 0.419$$

$$E = \rho V^2{}_p = 2.30 \times 10^6 \text{ metric tons/meter}^2$$

Horizontal movements u_x and u_y of the seismometer are converted into trace displacements on the Develocorder view screen with a magnification of about 5×10^4 at periods of 20 to 40 seconds; vertical displacements are magnified by 1×10^5. In addition, trace displacements are caused by seismometer tilting, with a conversion constant from figure 5 of about 1.3×10^7 m/radian at periods of 30 to 100 seconds.

Some estimates of steady-state forcing-function magnitudes are given below, using values and formulas already presented. Approximate distances are taken from the map of the area surrounding the Teledyne Geotech test well shown in figure 1. Suppose that a 25 metric ton truck passes on Shiloh Road at a minimum distance of 110 meters.

a. Horizontal displacement

$$u_y = \frac{1.419 \times 25 \text{ tons} \times 110 \text{ m}}{2\pi \times 2.3 \times 10^6 \text{ tons/m}^2} \left(\frac{60}{(125.3)^3} - \frac{.162}{125.3\ (125.3+60)} \right)$$

$$= 6.35 \times 10^{-9} \text{ m or } 0.32 \text{ mm on viewer}$$

b. Vertical displacement

$$u_z = \frac{1.419 \times 25}{2 \times 2.3 \times 10^6} \left(\frac{1.162}{125.3} + \frac{(60)^2}{(125.3)^3} \right) = 2.72 \times 10^{-8} \text{ m or } 2.72 \text{ mm on viewer}$$

c. Horizontal displacement due to tilt

$$\tau_y = \frac{1.4\ 9 \times 25 \times 110}{2\pi \times 2.3 \times 10^6 \times (125.3)^3} \left(2 - .838 - \frac{3 \times 60}{(125.3)^2} \right)$$

$$= 1.595 \times 10^{-10} \text{ radians or } 2.07 \text{ mm on viewer}$$

In the first example, the displacement would not be seen. However, the actual displacements of 6-10 mm on the vertical channel and 5-7 mm on horizontal traces compare favorably with the predicted values of examples 2 and 3.

Similar computations for an area such as Pinedale, Wyoming ($E = 7.86 \times 10^6$ tons/meter^2, $\sigma = 0.24$) indicate that at 60 m depth, vertical displacement and horizontal displacements due to tilt would be about one-third of the predicted values shown above.

4.2.2.4 Gravitational Attraction

Another potentential source of noise from the passage of larger trucks is the gravitational attraction between the KS mass and the truck. The force, F, exerted on one mass, m_1, by another m_2, and separated by distance, r, is given by

$$F = G \frac{m_1 m_2}{r^2} \tag{6}$$

where G is the gravitational constant. If equation (6) is solved using the weights (truck mass = 25T/9.8 m/sec^2) and distances given in the example above, and the mass of the KS horizontal seismometer, the force F is

$$F = \frac{6.67 \times 10^{-11} \frac{N.m^2}{Kg^2} \times .363Kg \times 2550Kg}{(125.3)^2 m^2} = 3.95 \times 10^{-12} N$$

This force is equivalent to an acceleration of 1.08×10^{-4} m/sec^2 on the KS mass or in terms of displacement at 40-second period, 4.39×10^{-10} m. Trace deflection at 50K magnification would be 0.02 mm. It is concluded then that gravitational attraction does not contribute to the cultural noise problem.

4.3 TILTS CAUSED BY FORCES ACTING DIRECTLY ON THE KS

4.3.1 Pressure

In the case of the triaxial instrument, the primary cause of noise was found to be due to apparent deformation in the stack as a result of convection-related pressure variations in the top of the borehole. Tests were run under this program to determine the effect of pressure on the KS package.

4.3.1.1 KS Sensitivity to Pressure Changes

In this test , microbarograph No. 1 was connected to sense pressure in the sealed borehole. A motor-driven pump was also connected to the borehole and near-sinusoidal pressure signals at periods of 6 to 150 seconds and 174 μbar p-p were introduced into the KS environment. Figure 9 shows a portion of the 16-mm film record during the test. The film traces show that the LPZ channel is not affected and that the LPN trace is most affected. The transfer function between pressure and equivalent ground motion on the LPN was then calculated to be approximately linear as shown in figure 10.

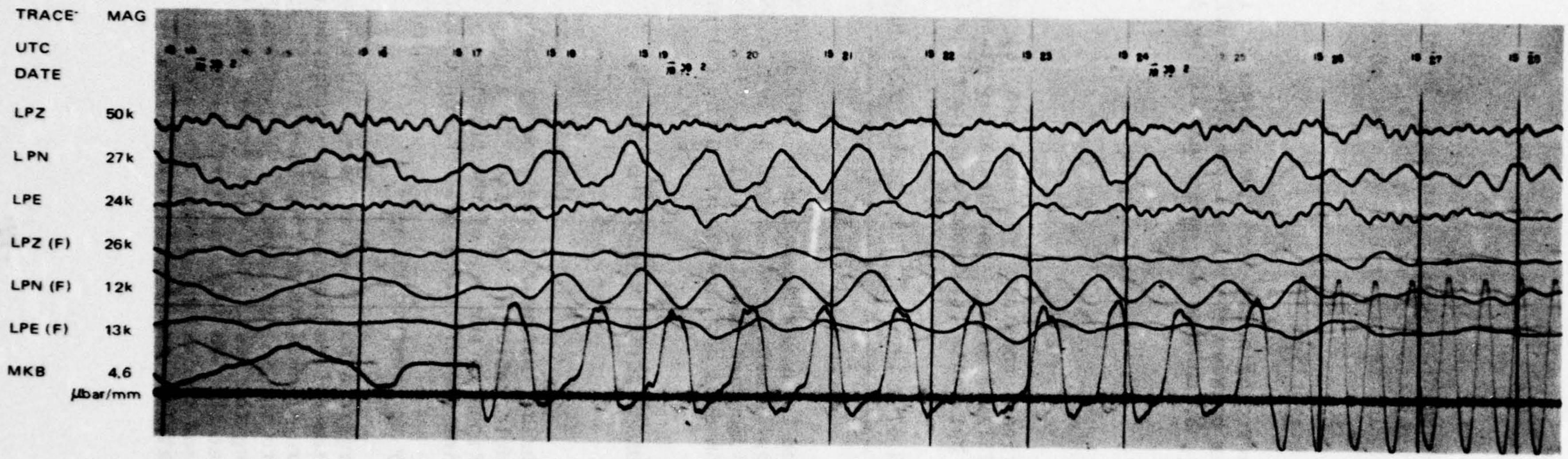


Figure 9. Reproduction of a 16 mm film recorded at Garland, Texas, on 1 April 1976, showing reaction of horizontal KS seismographs to sinusoidal pressure variations from a motor-driven pump attached to the borehole

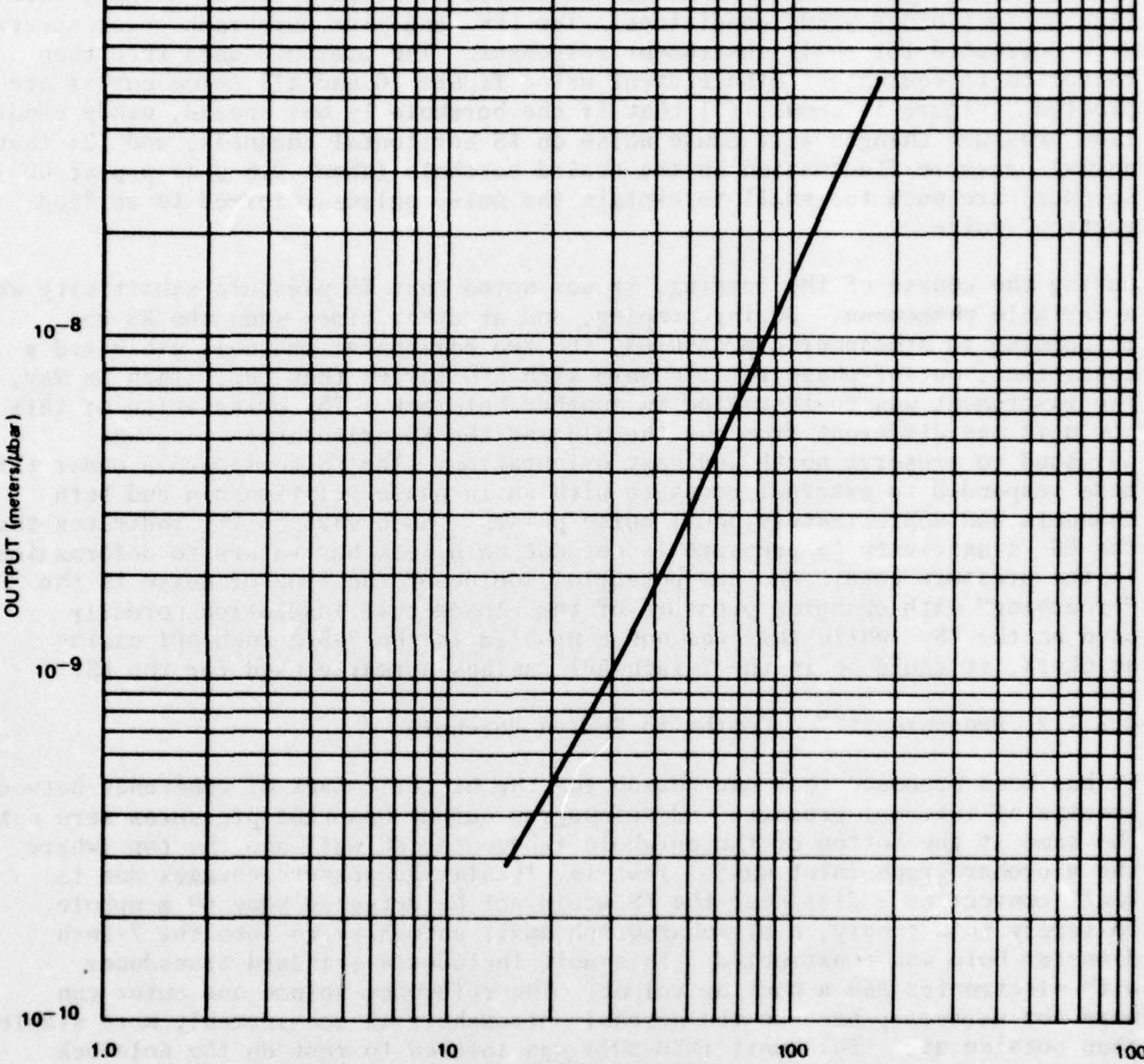


Figure 10. Transfer function of apparent horizontal displacement due to pressure acting on KS seismometer case, S/N 004

G 8962

Figure 11 summarizes these results. First, data were selected for a typical two-hour period during the night when winds and cultural activity were at low levels. The LPN and microbarograph were operating normally in the sealed borehole. Secondly, a sample of microbarograph data was selected from another day (17 May) when the instrument was connected to sense external air pressures fluctuations under windy conditions. The LPN and microbarograph power spectra were corrected for their instrument responses. The pressure data were then converted to equivalent displacement using figure 10 and all three curves are plotted. Figure 11 shows, (1) that if the borehole is not sealed, windy condition pressure changes will cause noise on KS horizontal channels, and (2) that normal pressure fluctuation in the sealed borehole (about 0.5 μbar p-p at 60 seconds) are much too small to explain the noise pulses referred to as "convection" noise.

During the course of the testing, it was noted that KS pressure sensitivity was a variable phenomena. During pumping, and at other times when the KS was responding to atmospheric pressures, the two horizontal channels exhibited a consistent, out-of-phase relationship with LPN larger than LPE. Then in May, the instrument was re-installed in another holelock. The orientation of this new unit was different from the the old and the KS orientation ring was adjusted to preserve north and east orientation. The KS horizontals under this mode responded to external pressure with an in-phase relationship and both channels had approximately equal noise pulses. Such variability indicates that the KS sensitivity to pressure is not due to a leak but rather to deformation in the pressure case. Another potential source of the type of noise is the "breathing" with changing pressure of the closed-cell insulation normally used on the KS. While this was not a problem in the 7-5/8 inch API casing at GL-TX, it could be in the 7-inch API casings normally used for the KS.

4.3.1.2 Pressure at Two Depths in Sealed Borehole

It has been proposed that one reason for the historic lack of coherence between spectra of internal pressure and seismogram output was that pressures were not the same at the bottom of the borehole (where the KS was) and the top (where the microbarograph inlet was). That is, localized pressure changes due to small convection eddies near the KS would not be detected some 60 m uphole. To verify this theory, a microbarograph small enough to go into the 7-inch diameter hole was constructed. This unit includes a standard transducer with electronics and a backing volume. The reference volume and outer can were not necessary because the borehole atmosphere is considerably more stable than outside air. This unit (MKB-BOT) was lowered to rest on the holelock (the KS had been removed for tests). The other unit was connected to sense upper borehole pressure changes. A two-hour sample was analyzed with the spectral programs. Figure 12 shows that the spectra of the two instruments are very nearly identical except at the longer periods where there are slight differences in response between the two instruments. Figure 13 a and b show the coherence squared and phase between the spectra. The high coherence and stable phase indicate that the instruments are responding to the same source(s) of signal.

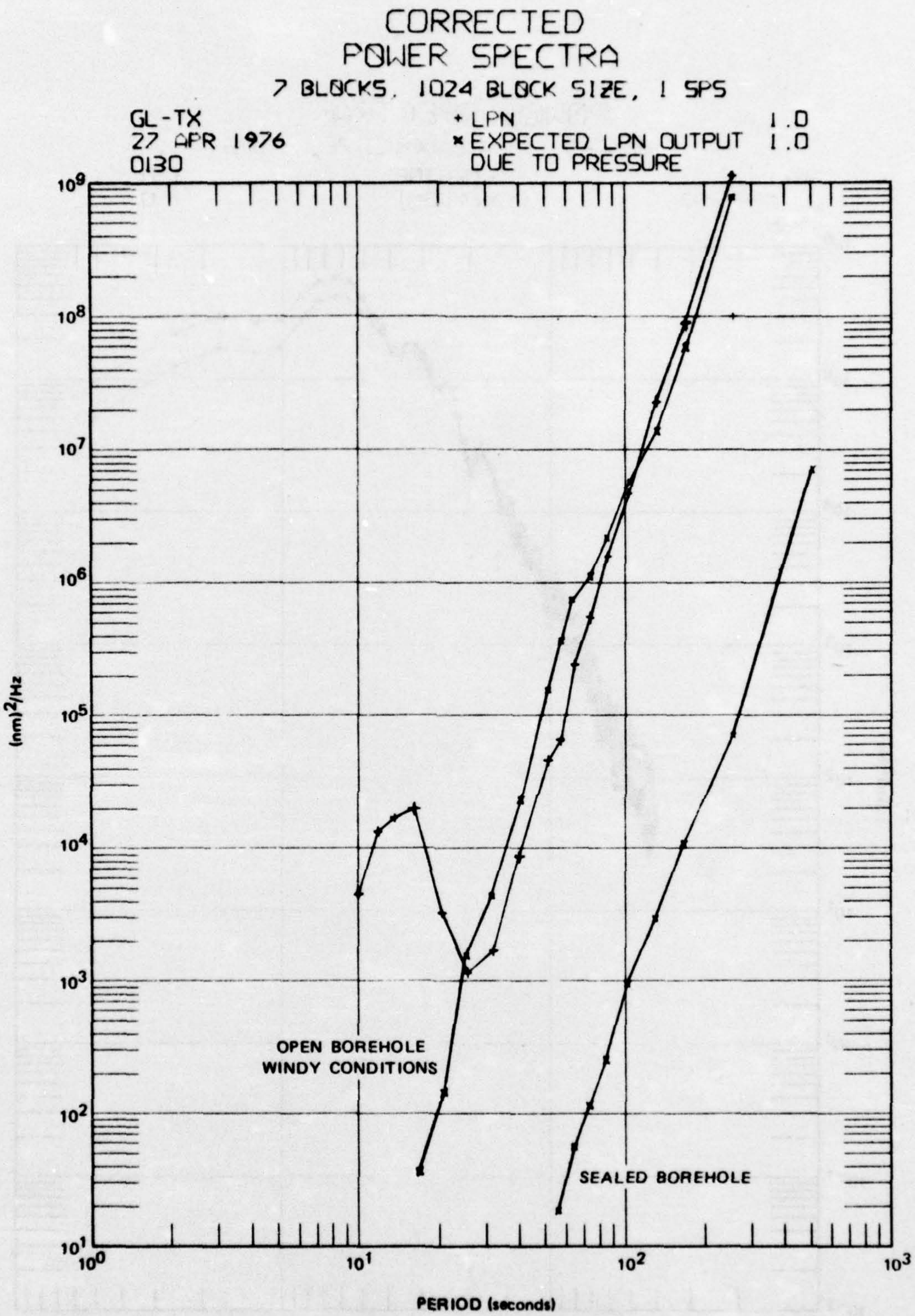


Figure 11. Power spectra of the background noise recorded by the long-period horizontal north (LPN) seismograph, corrected for instrument response. Also shown is the theoretically predicted noise contribution due to borehole pressure changes

G 8963

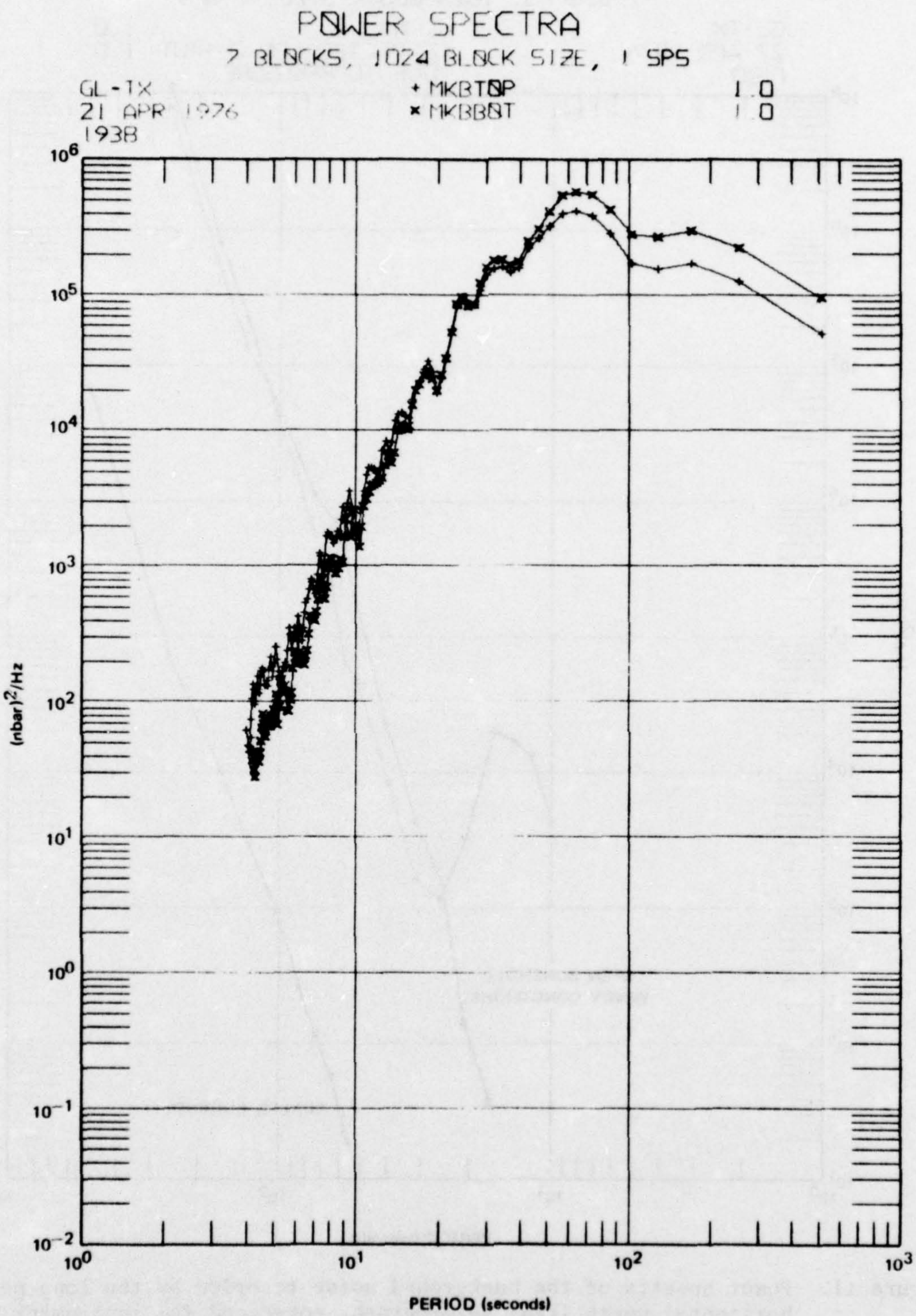
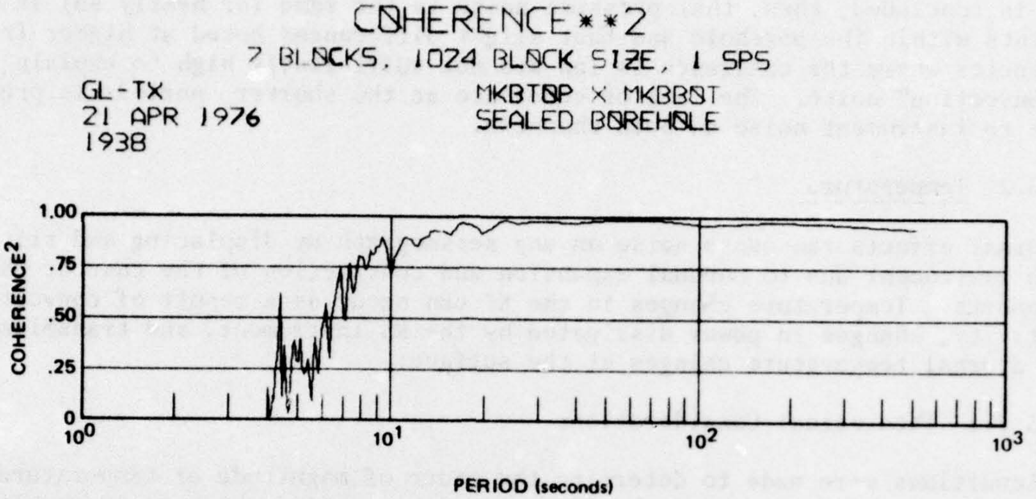
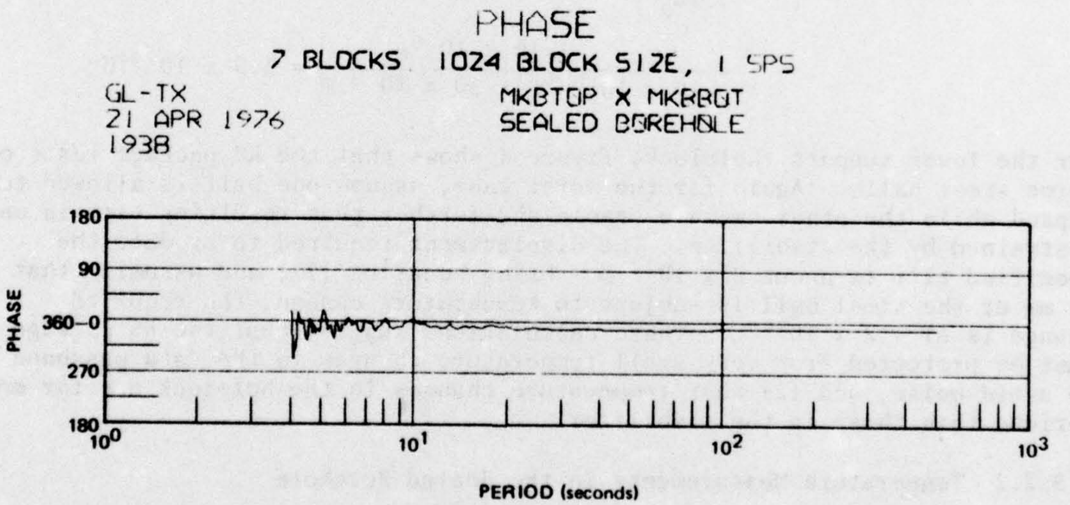


Figure 12. **Power spectra of internal pressure noise in the sealed bore-hole as sensed by MKBTOP at the top of the well and by MKBBOT at 60 m depth. Not corrected for instrument response**

G 8964



(a)



(b)

Figure 13. Coherence squared (a) and phase (b) between MKBTOP and MKBBOT when the instruments were separated by 60 m

G 8965

It is concluded, then, that pressure noise is the same (or nearly so) at all points within the borehole and that slight differences noted at higher frequencies where the coherence is low are not sufficiently high to explain KS "convection" noise. The lack of coherence at the shorter periods is probably due to instrument noise on both channels.

4.3.2 Temperature

Thermal effects can cause noise on any seismograph by displacing and tilting the instrument due to unequal expansion and contraction of the case or the supports. Temperature changes in the KS can occur as a result of convection activity, changes in power dissipated by the KS instrument, and transmission of diurnal temperature changes at the surface.

4.3.2.1 Theoretical Considerations

Calcualtions were made to determine the order of magnitude of temperature changes on various parts of the KS system as installed which would result in a measurable output. If a 5 mm trace deflection is assumed, a tilt of 3.85 x 10^{-10} radians is required. As a worst case estimate, assume that one stabilizer finger at the top of the package expands due to temperature and is unrestrained by the remaining stabilizer fingers. The displacement required to tilt the 3 m package is 1.16 x 10^{-9} m. The temperature change required is computed by

$$\Delta T = \frac{\Delta L}{\alpha L_o} \tag{7}$$

$$= \frac{1.16 \times 10^{-9} \text{m}}{10 \times 10^{-6}/°\text{C} \times 30 \times 10^{-3} \text{ m}} = 3.9 \times 10^{-3}°\text{C}$$

For the lower support (holelock) figure 4 shows that the KS package rests on three steel balls. Again for the worst case, assume one ball is allowed to expand while the other two are stable and further that resulting tilt is unrestrained by the stabilizer. The displacement required to produce the specified tilt is about 2 x 10^{11} m. Using equation (7), and assuming that 10 mm of the steel ball is subject to temperature change, the required change is $\Delta T = 2 \times 10^{-4}$°C. These calculations suggest that the KS package must be protected from very small temperature changes in the data passband to avoid noise, and (2) that temperature changes in the holelock are far more serious than those in the stabilizer.

4.3.2.2 Temperature Measurements in the Sealed Borehole

During the course of this study, temperature data were collected under several conditions in order to determine whether there were naturally occurring fluctuations capable of causing noise on the KS channels. First, data from the gradiometer shown in figure 4 were recorded. Then a fixed resistor was substituted for the lower thermistor to measure actual changes instead of gradients. Measurements were made both with the standard holelock and the insulated unit. A 3 m long gradiometer was installed above the KS package and operated several days. In all cases, the sensitivity of the sensor was

about 7 x 10^{-5}°C per mm trace deflection and the noise level was about 2 mm (1.5 x 10^{-4}°C). Measurements of trace deflection under all these conditions showed little data exceeding the channel noise level, with occasional pulses up to 1 x 10^{-3}°C. In addition to these measurements, spectral comparisons between the temperature channel and others were made for most of these conditions. The coherence squared between the spectra of temperature channel and that of any other channel (MKB or LPN) was generally low with only occasional peaks to the 0.2 to 0.3 level.

These data generally suggest that temperature changes may well be large enough to account for some of the KS noise. However, the resolution of the temperature channel is not adequate to make that statement with assurance.

In another test near the end of the program, several days of uninterrupted air temperature data were recorded on the strip chart recorder at a lower sensitivity (2.5 x 10^{-4}°C/mm) to observe long term (dc) effects. Analysis of the data showed diurnal fluctuations of about 2.5 x 10^{-3}°C around a mean of 19.9°C near the KS pilot, and inside the insulated portion of the holelock. The external temperatures varied from about 17 to 29°C and the borehole fluctuations lagged by about 14 hours. The fluctuations are considerably greater than expected. The theory shows that surface temperature changes should be attenuated exponentially with increasing depth in the earth. For example, a 10°C diurnal variation would be reduced to 1 x 10^{-3}°C p-p at a depth of 4 to 5 meters. Possible explanations for these high variations are (1) the steel casing (with its conductivity about 30 times greater than the earth) is transmitting them via conduction, or (2) moving air masses are carrying them by convection.

4.3.2.3 Tests Using Heaters

At this point in the study, it was concluded that if convections actually caused "convection" noise, the resulting air currents probably caused KS noise by changing the temperature of the mechanical supports. Resistive heaters were installed at three points near the KS instrument in an attempt to determine where potential thermal gradients would have the greatest effect. They were installed at the top of the instrument near the stabilizer fingers, in the pilot assembly just below the base of the KS, and on an insulating rod about 4 inches below the pilot. In all checks, 1 watt of heat was applied for a sufficient time to produce a noticeable effect on the KS channels. Figures 14 and 15 show the pulses produced on energizing the top and pilot heaters, respectively. In figure 14, heat was applied at 1903Z. The data indicate that the stabilizer apparently changed temperature slightly and tilted the KS package. The traces show that the instrument assumed a new equilibrium position and no obvious noise was noted until the heater was turned off several minutes later, when a similar pulse in the opposite direction was produced. In figure 15, heat was applied at 2015Z. Note that the pilot heater causes a major disturbance on the horizontal channels and the effect is almost immediate. The pilot heater test was repeated with the dc power reversed in order to eliminate electromagnetic effects and the results were very similar. In a long-term test where the pilot heater was on for several days, the instrument stabilized after a few minutes and operated normally with no obvious noise pulses until the heat was turned off. Neither of these heater tests produced data which are normally identified as "convection" noise,

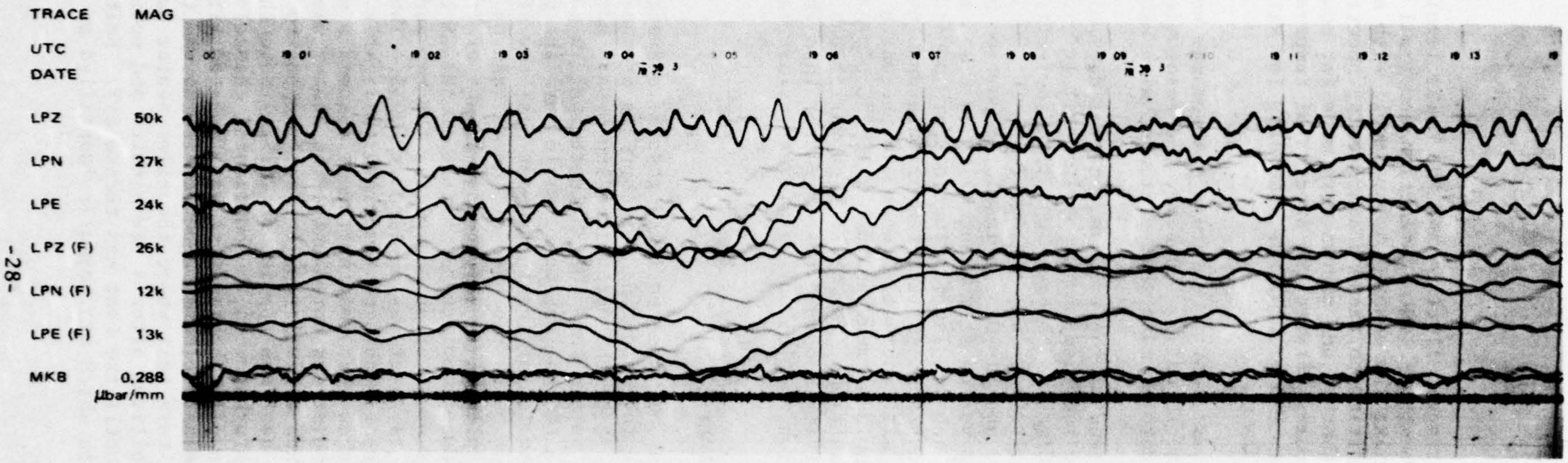


Figure 14. Reproduction of a 16 mm film recorded at Garland, Texas, on 2 April showing reaction of long-period horizontal seismographs to heat applied near stabilizer assembly at top of package

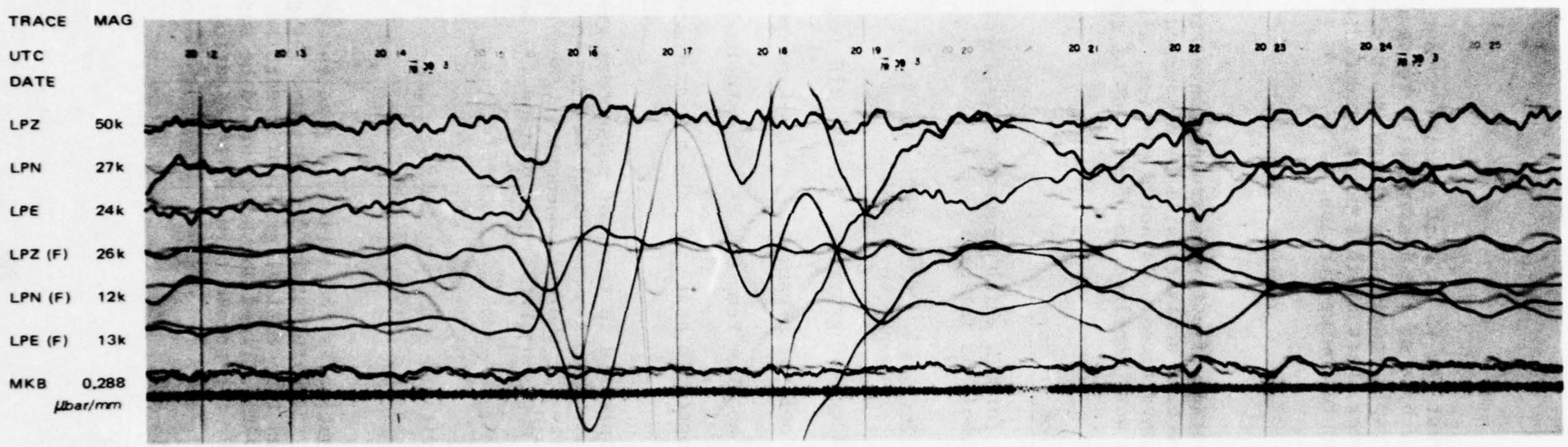


Figure 15. Reproduction of a 16 mm film recorded at Garland, Texas, on 2 April showing reaction of long-period horizontal seismographs to heat applied within pilot at base of instrument

but the tests verified that the KS is most sensitive to temperature changes in the holelock and/or lower base of the instrument. Tests using the lower heater did not indicate that a rapid temperature change was produced in the KS as with the other heaters. However, heat at this point produced apparent convection noise as discussed in the following section.

4.4 CONVECTIONS

In this section, the observed effects of assumed convections are discussed. Naturally occurring convection activity will be discussed first, followed by a discussion of forced convections. As noted earlier, all observations and tests under this program were confined to operations of the KS in the air-filled borehole.

4.4.1 Theory of Convection in Boreholes

Hales (1937) derived the formula which predicts a critical instability threshold for the fluid in any borehole as follows:

$$\frac{\Delta T}{\Delta z} \text{ critical } = \frac{g\alpha T}{C_p} + \frac{B\nu k}{g\alpha a^4} \tag{8}$$

where

g = accel of gravity	B = 216 (constant)
α = coeff of expansion	ν = kinematic viscosity
T = absolute temp	k = thermal diffusivity
C_p= specific heat	a = radius of hole.

The second term may be expressed in terms of parameters given by most tables as follows: the kinematic viscosity ν = absolute viscosity/density = μ/ρ and the thermal diffusivity k = thermal conductivity/density x specific heat at constant pressure = $\lambda/\rho Cp$, substituting, equation (8) becomes

$$\frac{\Delta T}{\Delta z} \text{ critical } = \frac{g\alpha T}{C_p} + \frac{B\mu\lambda}{g\alpha a^4\rho^2 C_p} \tag{9}$$

The first term of the equation is the adiabatic gradient of the fluid (10°C/km for dry air and 0.2°C/km for water at 20°C). Because the geothermal gradients are generally greater than the critical gradient predicted by the first term, most air filled and all water filled boreholes would be unstable except that the threshold is raised by the second term of the equation.

For any given fluid, note that the critical gradient is strongly dependent on the hole radius. Table 1 gives the calculated critical gradients for water and air for different hole sizes. Gretner (1967) states that the geothermal gradient for sedimentary areas such as Garland is seldom less than 1°F/100 ft or 0.018°C/m; the measured gradient at the Pinedale, Wyoming borehole is about 0.01°C/m. Therefore, the table shows that water-filled holes with diameters greater than 7 cm are unstable and that air-filled holes through 16 cm should be stable.

Table 1. Critical gradient for water and air, various hole sizes

Tube diameter	Critical gradient, water	Critical gradient, air
2 cm (3/4 in.)	1.49°C/m	146°C/m
7 cm (2-3/4 in.)	9.93×10^{-3}°C/m	0.97°C/m
16 cm (Std 7-in. API casing)	5.64×10^{-4}°C/m	0.045°C/m
33 cm (Std 13-5/8 in. API casing)	2.2×10^{-4}°C/m	0.012°C/m

These calculations for water are in general agreement with the findings of other authors. Diment (1967) shows that the fluid in nearly all deep wells should be unstable. Indeed, he measured continual temperature fluctuations up to 0.05°C in amplitude and between 1 and 50 minutes in period at most depths in such a well filled with water. (His instruments were incapable of following fluctuations of shorter periods.) Gretener (1967) obtained similar results. Both of these workers found indications that the convection eddies believed to exist were comparable to the hole diameter in vertical extent. Both Gretener (1967) and Garland and Lennox (1962) showed that the observed thermal instabilities could be stopped by reducing the hole diameter by means of a cemented-in inner casing or a loose bundle of tubes. The critical diameter corresponded in order of magnitude to that predicted by Hales' formula. Finally, the results of operating the KS in water reported by Douze and Sherwin (1975) strongly suggest that instability in the 9-5/8 in. water-filled casing at Pinedale causes the 100-200 second tilt noise seen on horizontal data traces.

The implications for a KS operating in air are not as clear-cut as in the case of water. For operation in air, the effect of the approximate 3-watt dissipation of the KS electronics must be added to the effect due to heat flow. While this additional heat could cause a nominally stable borehole to become unstable, it is possible that the activity thus produced would be above the instrument where tests discussed above indicate that there would be little effect on the KS.

4.4.2 Natural Convections in the Sealed Borehole

One of the goals of this study was to identify, if possible, the source(s) of naturally occurring convection activity in a sealed borehole. The microbarograph has proved to be an effective instrument in detecting the presence of convections due to the pressure changes which they produce.

One test necessary during this program to establish a base was verification of prior tests involving upper-borehole convections arising due to cooling the wellhead. Experience at the ALPA and here in Garland has been to install insulation in the top few meters of the borehole to prevent this pressure noise. During early June when the diurnal fluctuation was about 15°C, the 1.5 m long foam plug installed at the top of the well was pushed down to leave a void about 25 cm long. The borehole was again sealed and the microbarograph was connected to sense borehole pressure. Figure 16 is a reproduction of a portion of a Helicorder record which shows a dramatic increase in almost sinusoidal pressure noise during the night. The noise at 2330Z is typical of normal pressure noise throughout the tests. By 0100Z small fluctuations at 0.04 μbar, p-p, and 18-second period are beginning to build up. The peak of the activity appears to be about 6 μbars, p-p or 150 times higher than normal noise. By 1300Z, or about local sunrise, the activity has begun to decrease rapidly. This phenomenon repeated itself for several days. Note that the pressure recorded is not large enough to cause a measurable output on the KS horizontal based on data from figure 10. At this time, the borehole was opened and the void was filled to the top with loose insulation. Figure 17 shows the improvement for a similar time period as in figure 16. The period of very low level noise beginning at 0600Z shows fluctuations of about 0.01 to 0.02 μbar, p-p, the approximate noise level of the instrument. Figure 18 compares the spectra of day and nighttime interval borehole pressure noise from an earlier period with the insulating plug installed. Note that there is little difference between the two periods.

Figure 17 clearly shows low-level pressure noise in the sealed borehole at a level up to 0.2 μbar, p-p, and 40-80 second period. It is just such low-level pressure activity which this program hoped to identify as convection noise. To verify that such noise is not a result of external pressure activity (either due to leaks or due to induced volume changes in the borehole) or due to added heat from the KS instrument, spectral comparisons were made between the inside and outside microbarographs while the KS instrument was out of the borehole for noise tests. Figure 19a shows the coherence squared between these instruments during the evening hours when there was little borehole pressure activity and low winds. There is virtually no coherence for all periods. Figure 19(b) shows coherence squared for a period beginning nine hours later when the inside microbarograph was sensing apparent upper borehole pressure activity, again there is virtually no coherence except for the small peak between 40 and 50 seconds.

As mentioned in paragraph 4.3.2 above, spectral comparisons between the inside microbarograph and the temperature sensor, and the KS seismograph did not indicate any linear relationship between any of the data sets. In short then, the tests failed to absolutely identify convection activity as the cause of low-level pressure noise inside the sealed borehole. However, it is still thought at convection cells somewhere or everywhere in the hole are the most likely cause.

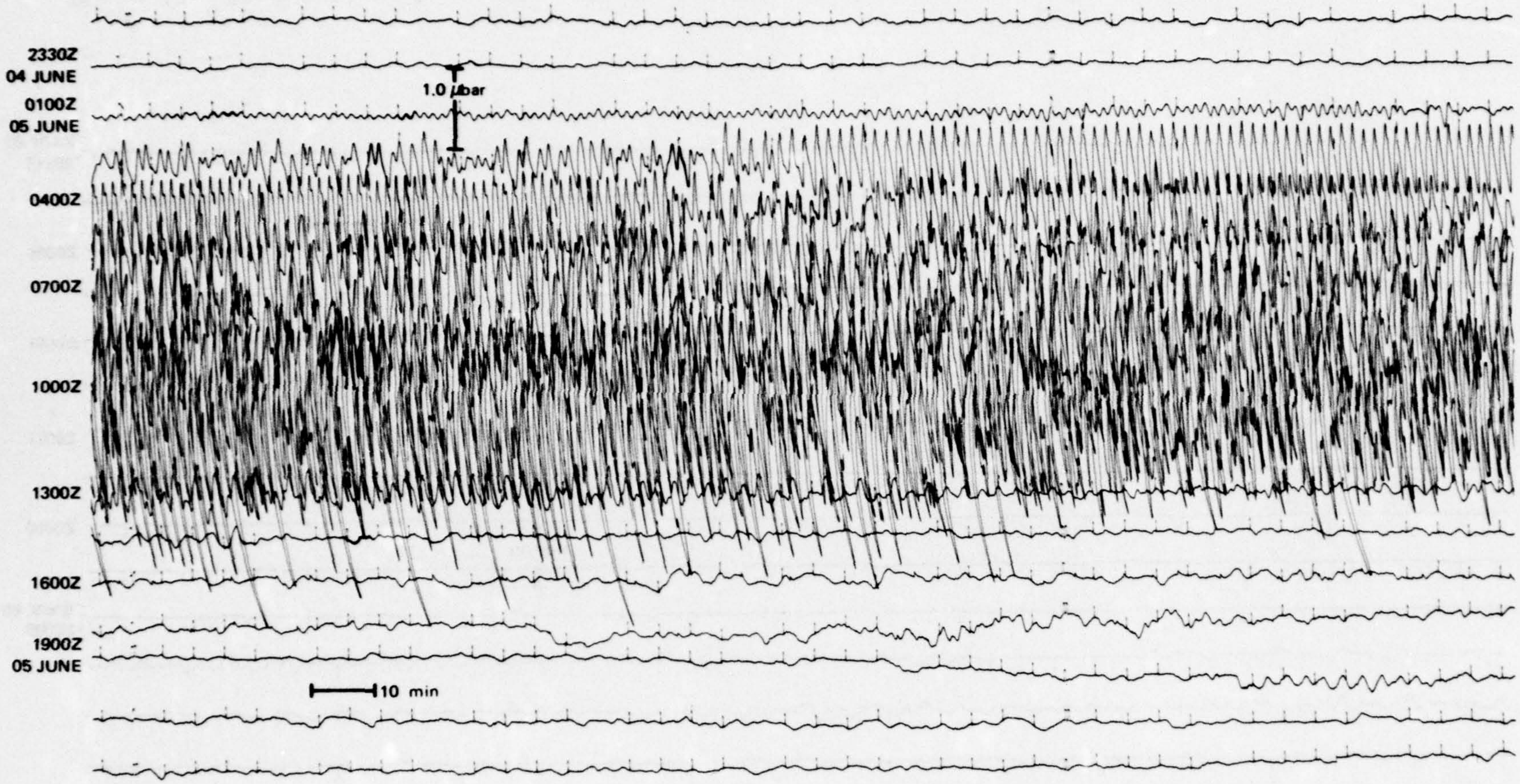


Figure 16. Reproduction of a portion of a Helicorder record of 4 June 1976, showing naturally occurring convection-related pressure activity inside the sealed borehole. A volume about 1-foot below the wellhead seal was not filled with insulation

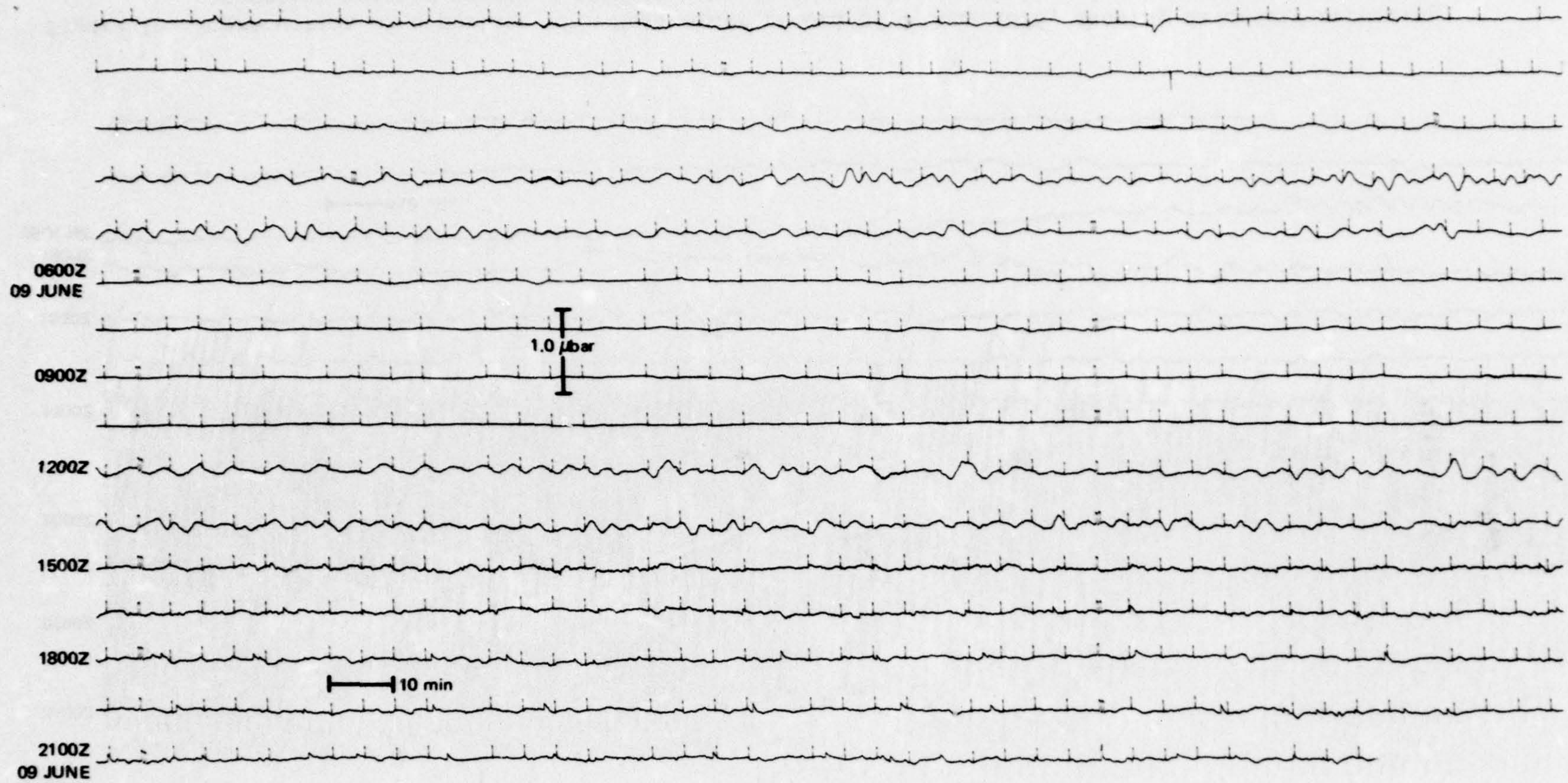


Figure 17. Reproduction of a portion of a Helicorder record of 8 June 1976, showing a significant reduction in borehole pressure activity sensed by the microbarograph when the upper portion of the borehole was completely filled with insulation

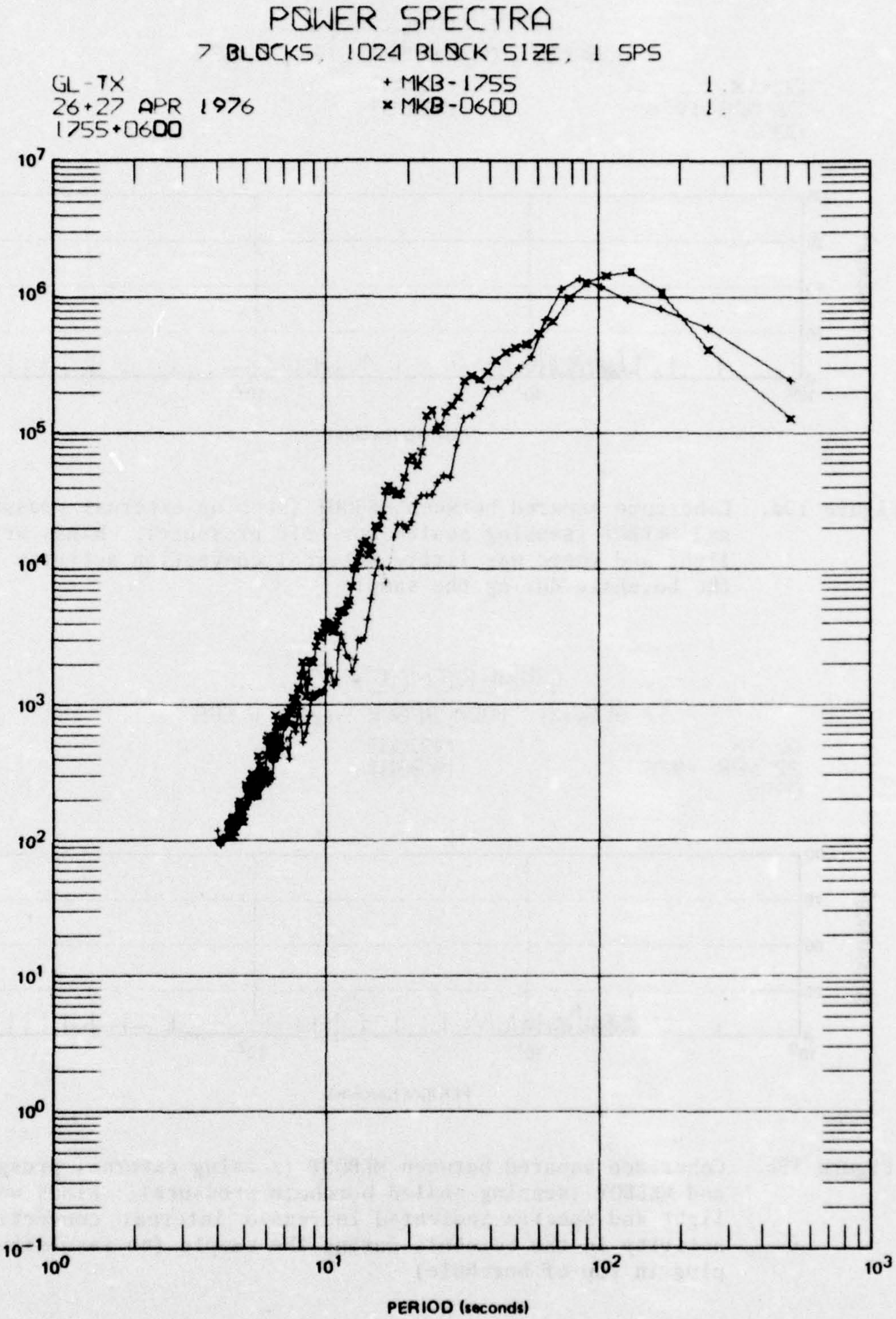


Figure 18. Power spectra of internal pressure noise in the sealed borehole as sensed by the microbarograph showing little difference in level between day and night when insulating plug is installed in top of borehole

G 8966

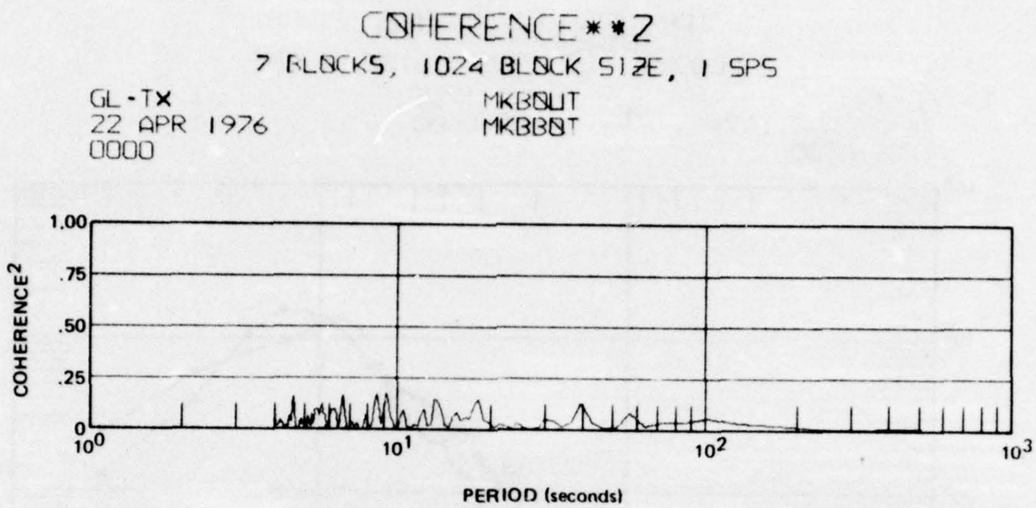


Figure 19a. Coherence squared between MKBOUT (sensing external pressure) and MKBBOT (sensing sealed borehole pressure). Winds were light and there was little internal convection activity in the borehole during the sample

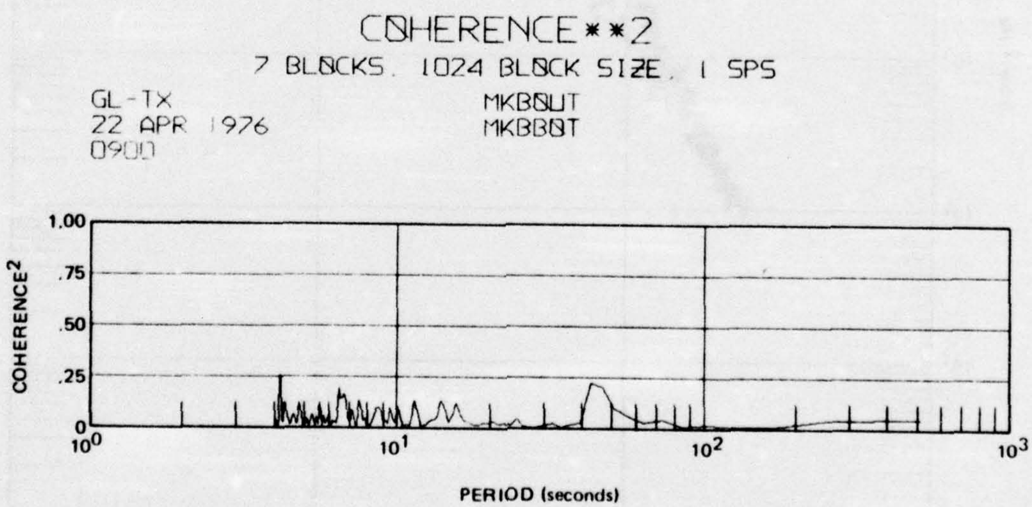


Figure 19b. Coherence squared between MKBOUT (sensing external pressure) and MKBBOT (sensing sealed borehole pressure). Winds were light and spectra indicated increased internal convection activity in the borehole during the sample (no insulating plug in top of borehole)

G 8967

4.4.3 Forced Convections in the Sealed Borehole

Two test series were run in which convection activity was forced by applying 1-watt to the lower heater beneath the instrument's holelock. It was thought that heat applied at this point would be more conductive to generating convections than were the top and pilot heaters, because there was adequate space above the heater to establish an inverse thermal gradient. In the first series, the holelock was a standard unit, and in the second series, the insulation shown in figure 4 had been added.

4.4.3.1 Heating Tests with Standard Holelock

The first test series was intended to show the effects of heat and/or convection activity on the bottom of the unprotected holelock. In one of these tests, power at the 1-watt level was applied to the heater for one hour during a period when cultural activity is usually low. Figures 20 through 22 show representative portions of the film data during this test. Figure 20 shows all channels operating normally before the test. Note that the horizontal KS channels are relatively free of long-period noise. In figure 21, the horizontal noise level has increased to about 200 nm p-p at 40 seconds; the microbarograph shows a slight increase in 6-8 second noise at about 0.08 μbar and no obvious change at the longer periods. The noise buildup on the horizontal channels began within five minutes after applying the heat. Note also in figure 21 that there is no consistent phase relationship between the noise on LPN and LPE, which indicates that the disturbance is apparently random in nature. Figure 22 shows that all traces had returned to normal operation within 15 minutes after the heat was turned off. This test was repeated several times and the results were almost identical. Noise on the horizontal channels began within five minutes in all cases.

Figures 23 and 24 show the spectra for the gradiometer and LPN channels under similar no-heat (0600Z) and heat (0530Z) conditions as in figures 20-22. In this case, the heat was left on for several hours in order to collect enough data for spectral analysis. The top thermistor of the gradiometer indicated that the air temperature rose to 25.3°C during long-term heating. Figure 23 shows that, during heating, the gradiometer signal increases in power by factors of 10 to 50 in the period range from 20 to 512 seconds. Figure 24 shows a similar increase at the long periods on the LPN channel, but only by a factor of 10 (about 3 in amplitude). The spectra (not shown) for the microbarograph during the same time periods showed virtually no difference between operation under the two conditions.

Figure 25 shows two examples of the coherence between channels during heating. The coherence between LPN and the microbarograph (figure 25a) is low except for the peaks at about 55 and 170 seconds. These peaks are significant and indicate some linear relationship between at least a portion of the noise on the two channels. This coherence may not be related to heating. The coherence between these channels for the no-heat (0600Z) sample (not shown) was very low at all periods, yet another no-heat sample on the same day (0130Z) showed significant coherence (0.25-0.36) at periods greater than 100 seconds. Figure 25b shows the coherence between the LPN and gradiometer channels. Significant peaks occur only near 6 and 12 seconds; except for these, there is no apparent relationship between these channels. The coherence between the microbarograph

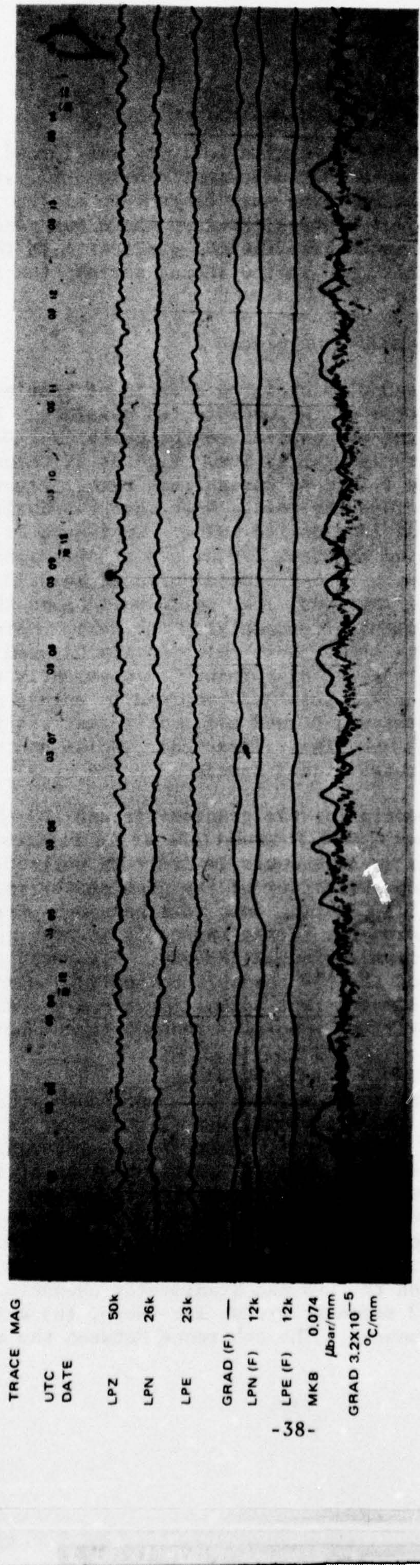


Figure 20. Reproduction of a 16 mm film recorded at Garland, Texas, on 30 April 1976, showing a representative sample of background noise on seismic traces prior to applying heat below sensor

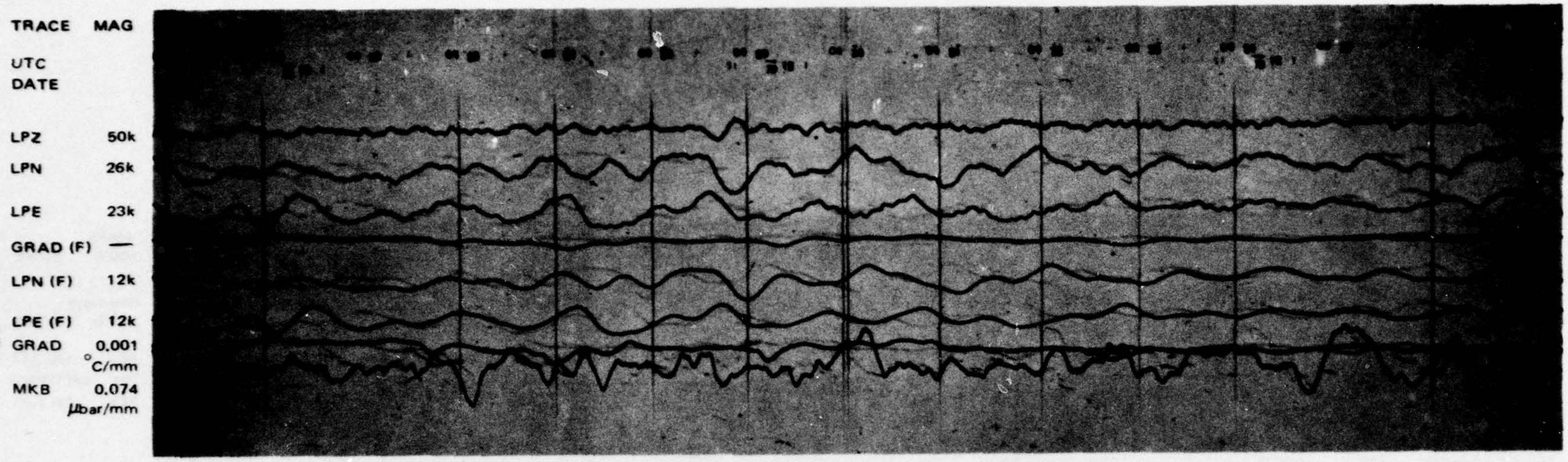


Figure 21. Reproduction of a 16 mm film recorded at Garland, Texas, on 30 April 1976, showing a buildup of long-period noise on both horizontal components without an apparent change in the background noise on the vertical component. At 0355Z power had been applied to generate 1 watt of heat in heater No. 2 below the holelock

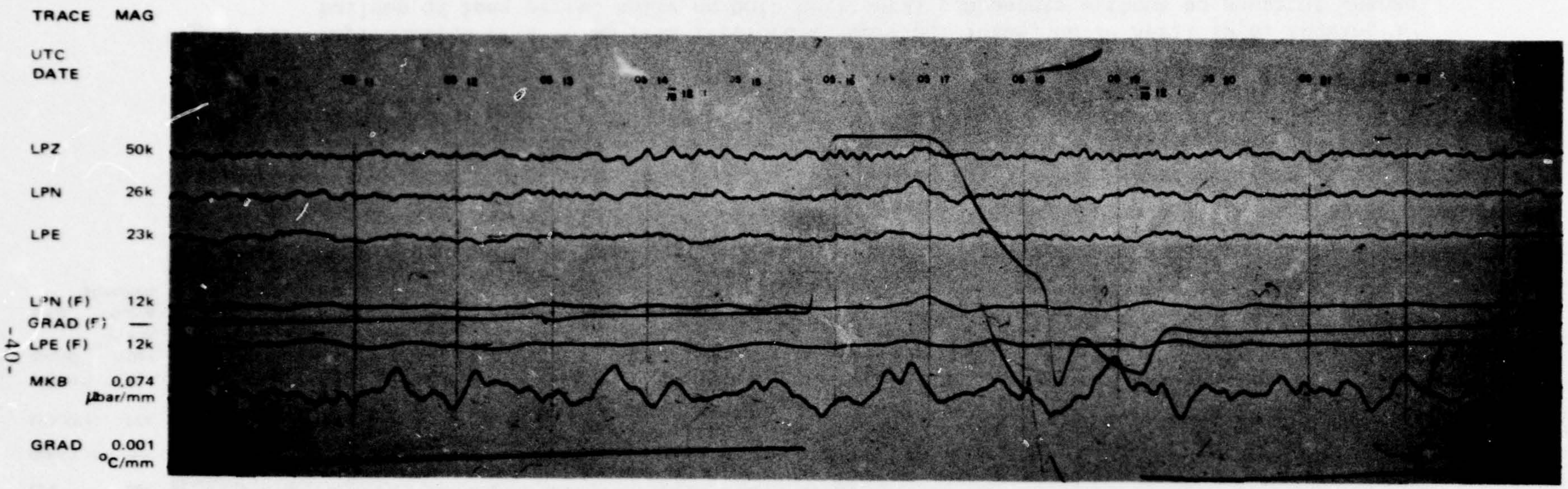


Figure 22. Reproduction of a 16 mm film recorded at Garland, Texas, on 30 April showing background noise on LP horizontal components returning to normal within 15 minutes after heat had been turned off at 0455Z

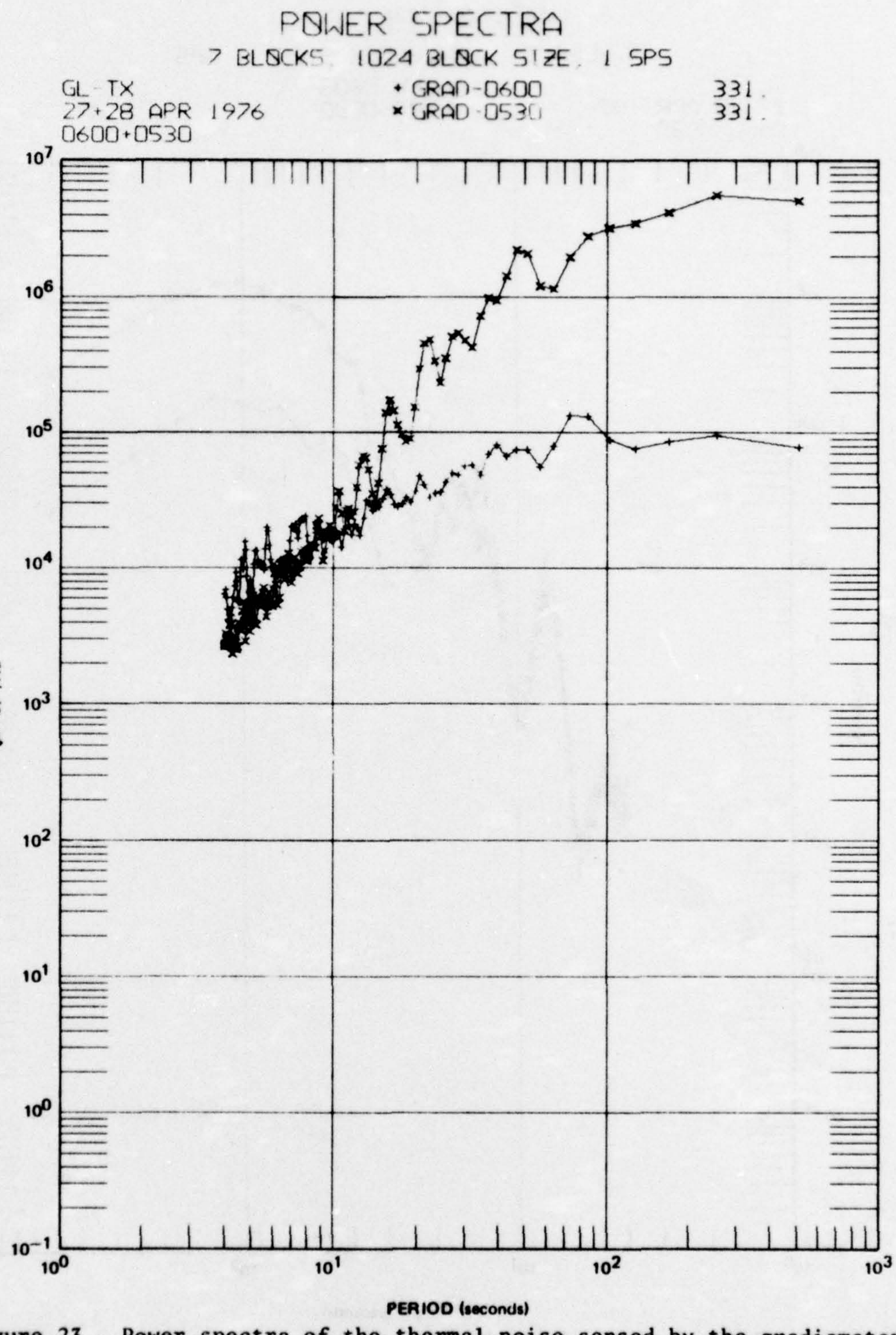


Figure 23. Power spectra of the thermal noise sensed by the gradiometer under two operating conditions. At 0600Z on 27 April, operations were under normal nighttime conditions; at 0530Z on 28 April, 1 watt of heat was being dissipated in heater No. 2

G 8968

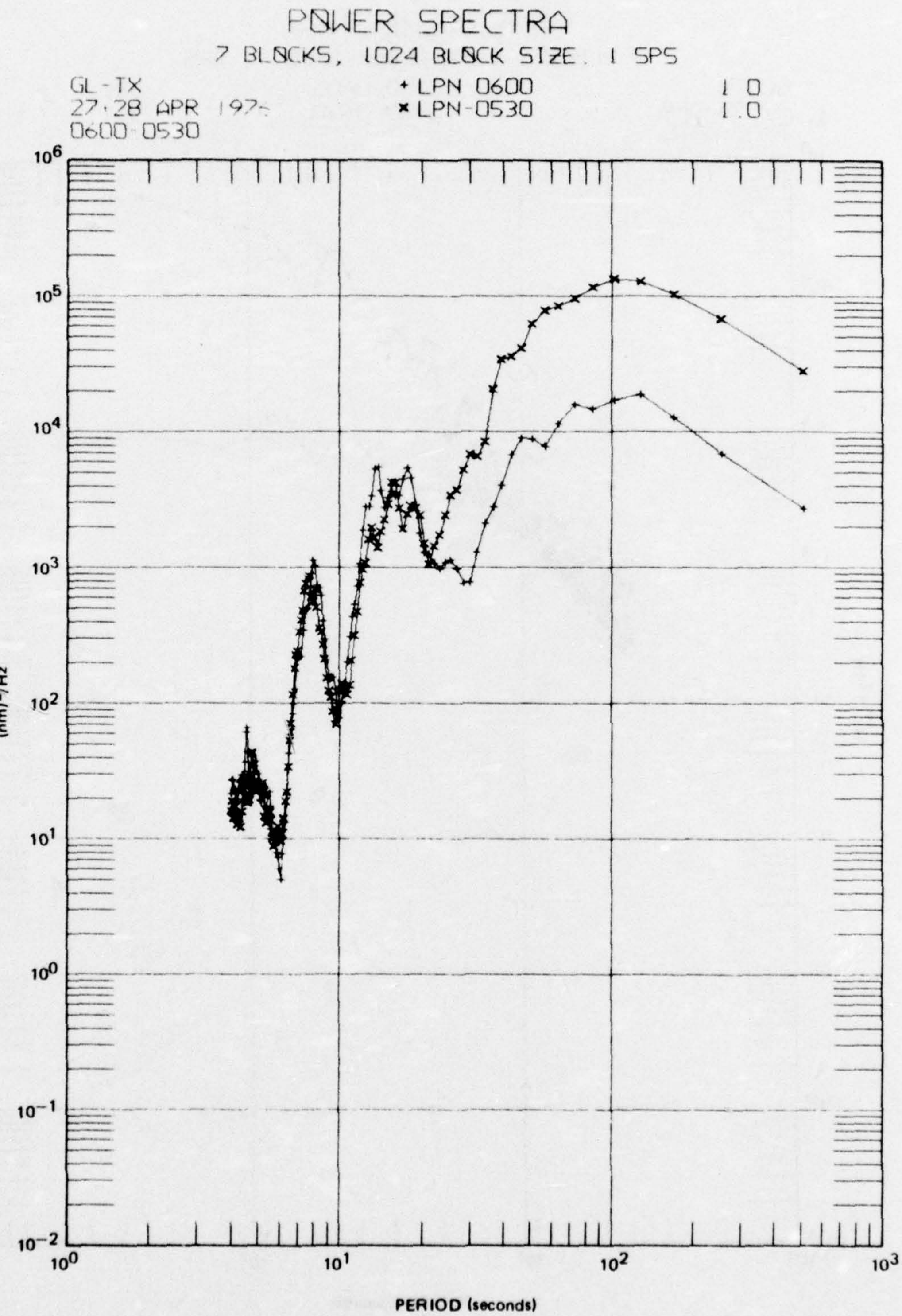


Figure 24. Power spectra of the background noise recorded by the long-period north (LPN) seismograph under two operating conditions. At 0600Z on 27 April, operations were under normal nighttime conditions; at 0530Z on 28 April, 1 watt of heat was being dissipated in heater No. 2

G 8969

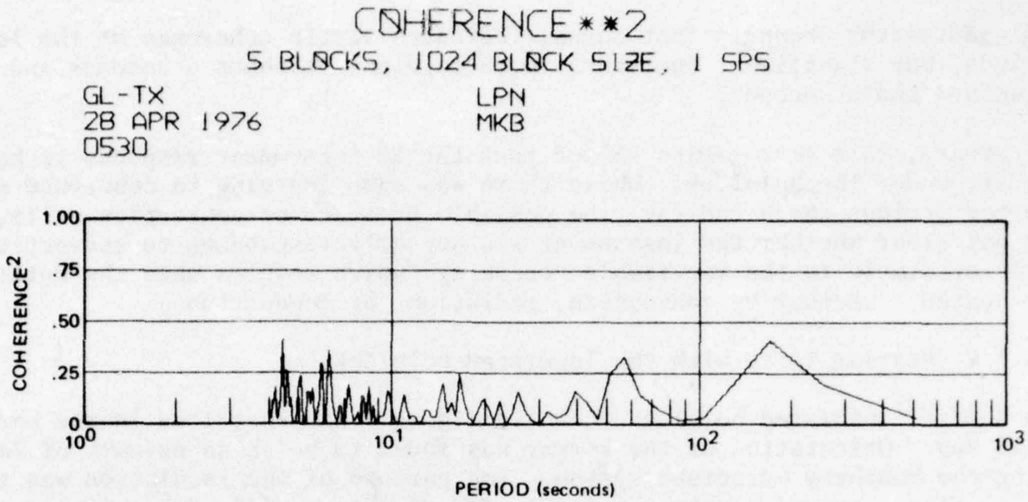


Figure 25a. Coherence squared between LPN and the microbarograph when heat was being dissipated in heater No. 2

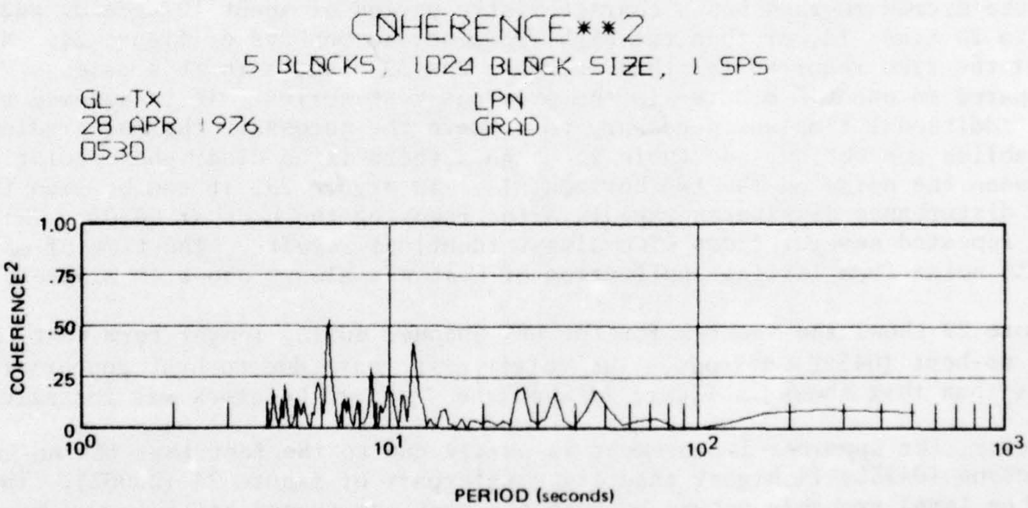


Figure 25b. Coherence squared between LPN and the gradiometer when heat was being dissipated in heater No. 2

G 8970

and gradiometer channels (not shown) indicates little coherence at the longer periods, but significant increases (0.25 to 0.65) at about 6 seconds and again between 4 and 5 seconds.

In summary, this test series showed that the KS instrument responds to heating the air under the holelock. While there was some increase in coherence at the shorter periods which indicate the possible presence of convection cells, it was not clear whether the instrument was actually responding to convection cells or simply to the inevitable "creaking" which results when the metal parts are heated - whether by convection, radiation, or conduction.

4.4.3.2 Heating Tests with the Insulated Holelock

The special insulated holelock shown in figure 4 was installed in the borehole on 13 May. Orientation of the keyway was found to be at an aziumth of 347° using the Humphrey Gyroprobe system. The purpose of the insulation was two-fold: first, to reduce the potential effects of naturally-occurring convections below the holelock and second, to study the changes brought about by reducing the effective diameter of the volume of air being heated from 18 to 7 cm.

A series of tests was conducted similar to those discussed in paragraph 4.4.3.1 above. Figures 26 through 28 show representative samples of the film data during one of several short-term heating tests. As before, figure 26 shows that all traces are relatively quiet prior to the application of heat at 0330Z. Figure 27 shows all channels quiet until 0409Z when both horizontals and the microbarograph sharply began responding to convection activity. The disturbance on the microbarograph has a characteristic period of about 12 seconds and is 10 to 20 times larger than the high frequency components of figure 21. Note that the time required for this increase was 39 minutes in this case as compared to about 5 minutes in the previous test series. It is assumed that the additional time was necessary to achieve the necessary thermal gradient to establish convection (see table 1). Again there is no clear phase relationship between the noise on the two horizontals. In figure 28, it can be seen that the disturbance dissipates rapidly after removing the heat at 0430Z. This test was repeated several times with almost identical results. The time of onset of KS noise from initial application of heat was always about 40 minutes.

Figure 29 shows the spectra for the LPN channel during longer-term heat (2115Z) and no-heat (0435Z) periods. The relative increase due to heat appears to be less than that shown in figure 24 when the standard holelock was installed.

However, the apparent improvement is partly due to the fact that the no-heat spectrum (0435Z) is higher than its counterpart of figure 24 (0600Z). This higher level probably occurs because the heat was turned off only two hours before the 0435Z sample began and there may have not been sufficient time for equilibrium to be reestablished. The noise increase due to heat apparently occurs only at periods longer than 20 seconds; this is consistent with the data of figure 24. As was the case in the prior test series, the spectra (not shown) for the microbarograph during the same time periods showed little difference between operation under the two conditions.

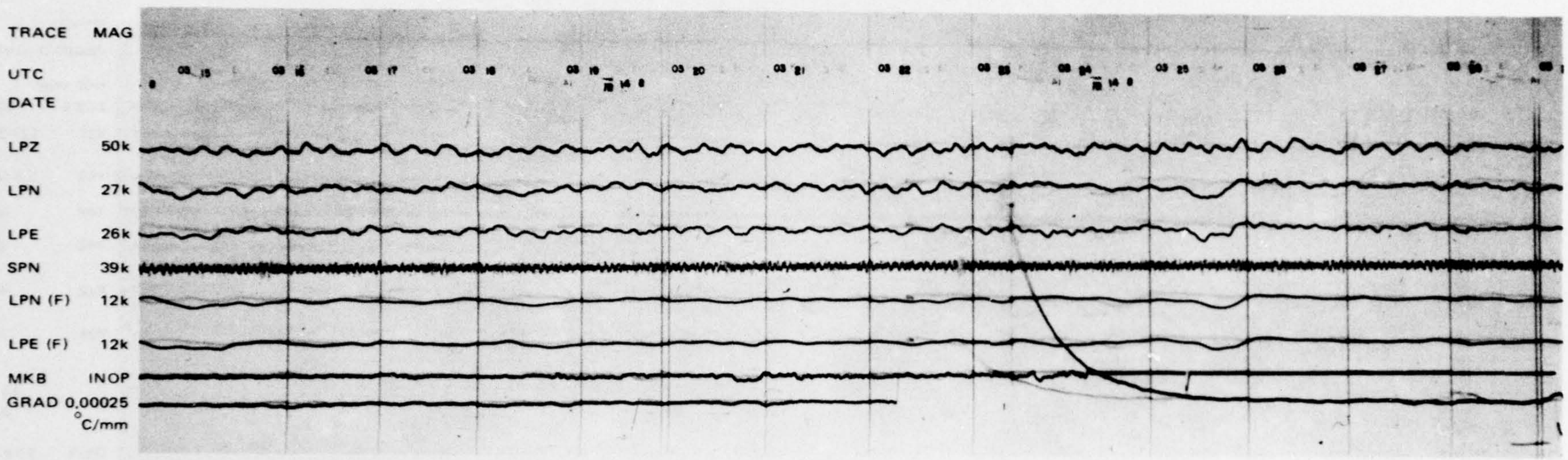


Figure 26. Reproduction of a 16 mm film recorded at Garland, Texas, on 27 May 1976, showing a representative sample of background noise on the seismic traces prior to applying heat below sensor

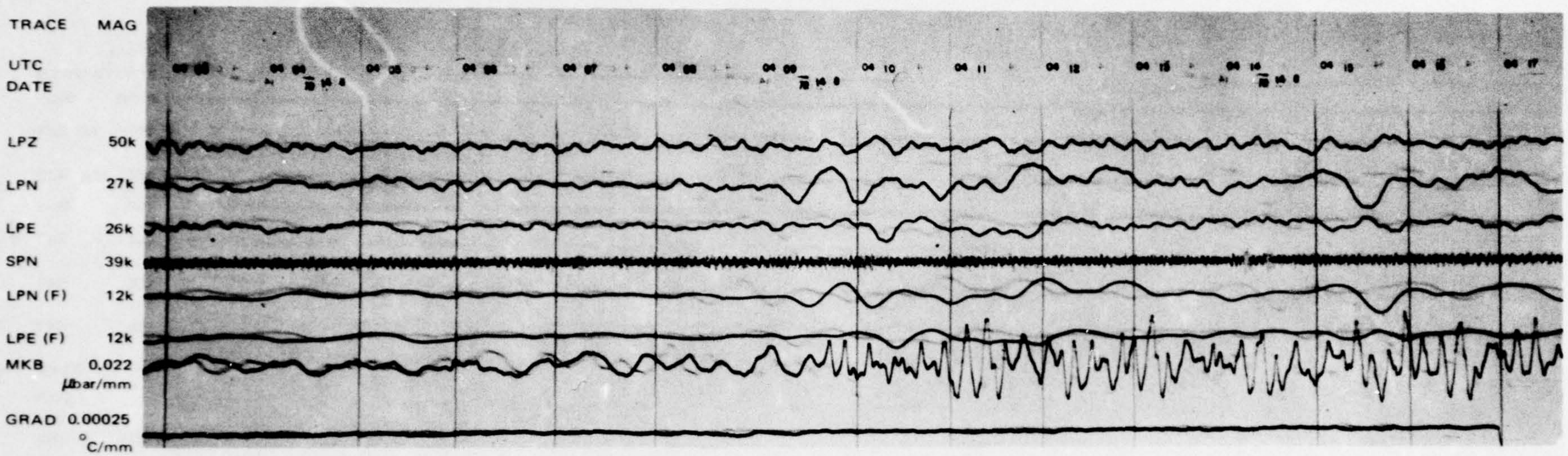


Figure 27. Reproduction of a 16 mm film recorded at Garland, Texas, on 27 May 1976, showing a very rapid buildup of noise in long-period horizontal and microbarograph traces (0409Z) resulting from the dissipation of 1 watt of heat in heater No. 2 which began at 0330Z. Special insulated holelock had been installed

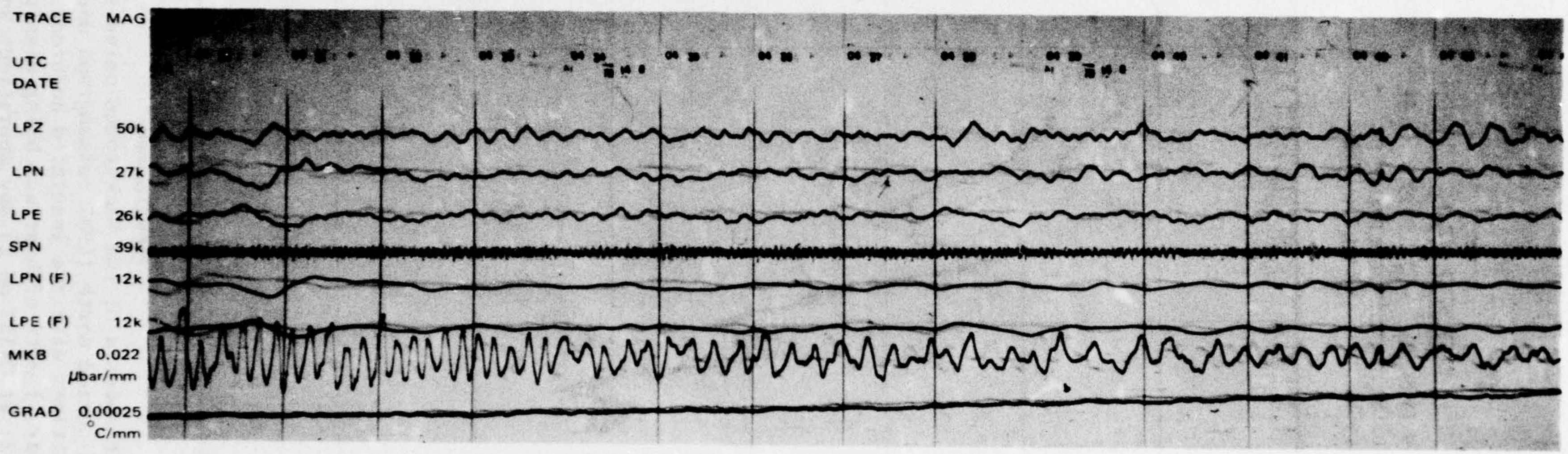


Figure 28. Reproduction of a 16 mm film recorded at Garland, Texas, on 27 May 1976, showing the decrease in seismic and pressure noise after turning off heat at 0430Z

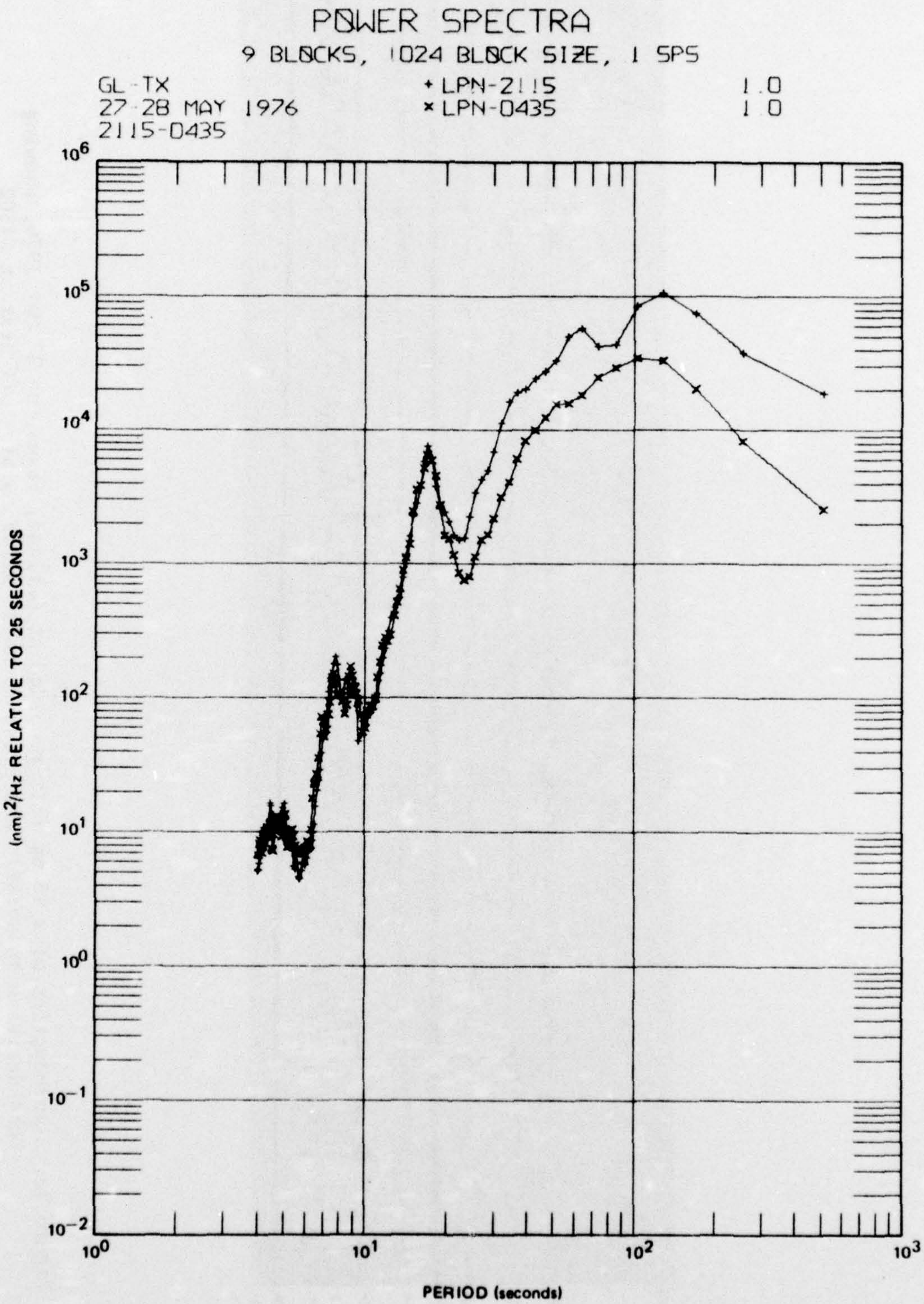


Figure 29. Power spectra of the background noise recorded by the long-period north (LPN) seismograph under two operating conditions with the insulated holelock. At 2115Z on 27 May, 1 watt of heat was being dissipated in heater No. 2; at 0435Z on 28 May operations were under normal nighttime conditions

G 8971

The coherence squared plots, figure 30, show there is virtually no linear relationship between either the LPN and the temperature channel, or LPN and the microbarograph. However, the simultaneous onset of noise on both microbarograph and LPN channels indicate that, while there may be no linear relationship, both instruments are almost surely responding to the same disturbances.

Figure 31 shows the spectra and figure 32 shows the coherence and phase for the temperature and microbarograph channels during the long-term heating test. Note that both spectra have strong peaks at about 11 seconds. The coherence is also very high near this period and remains higher than usual out to about 100 seconds. The phase between the two channels is near 180° for the periods of high coherence. These plots are significant in that they indicate a linear relationship between pressure noise and temperature noise under conditions (heating) when theory predicts that convections should take place. It is concluded then that slowly moving cells of warm air do exist when there is an adequate inverse thermal gradient, and that these moving air masses can cause measurable pressure changes in the sealed borehole. Given that convection cells exist in a closed borehole, the data thus far indicate that noise can be produced on KS horizontals by these cells and, furthermore, that the cause-effect relationship is not simple or predictable.

4.4.4 Reduction of Convection Activity by Changing Borehole Atmosphere

As paragraph 4.4.1 shows, equation (9) indicates that, for a given tube size, the critical gradient is strongly dependent on the density of the fluid since it is squared. It was therefore postulated that substitution of a light gas for at least a portion of the air in the borehole might be an effective method of reducing potential convection activity. Table 2 shows the potential improvement predicted by substituting a 50-percent air-helium mixture or pure helium for the normal air in the borehole.

Table 2. Critical gradients for air-helium mixture and helium at 0°C various tube sizes

Tube diameter	Threshold gradient, air-helium mixture	Thermal gradient, helium
2 cm	531.0°C/m	9500.0°C/m
7 cm	3.60 °C/m	63.3°C/m
16 cm	0.187°C/m	2.32°C/m
33 cm	0.064°C/m	0.130°C/m

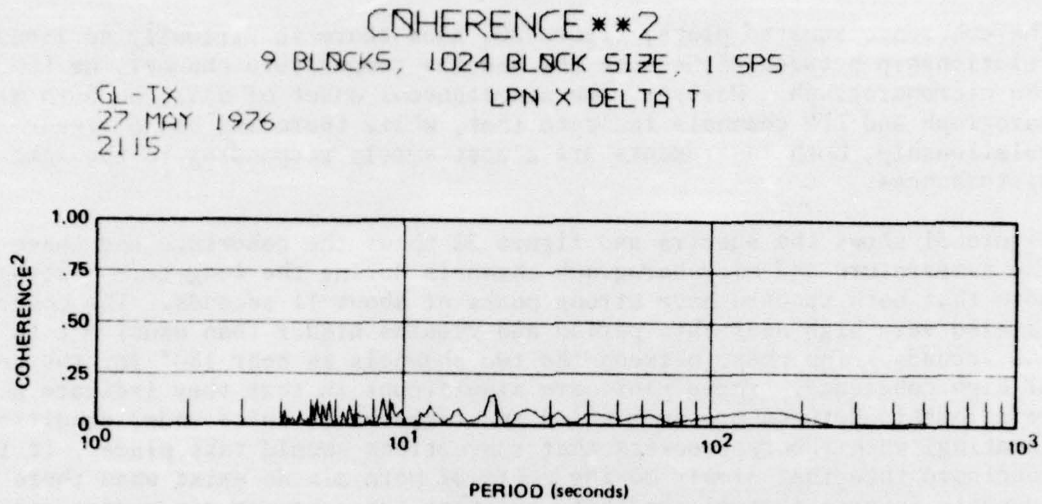


Figure 30a. Coherence squared between LPN and the temperature (Delta T) channel when heat was being dissipated in heater No. 2

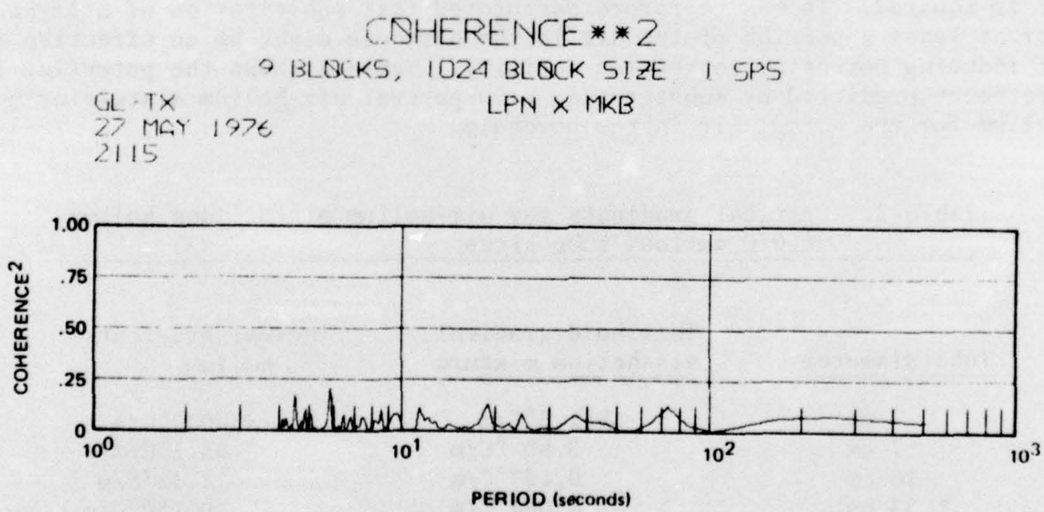


Figure 30b. Coherence squared between LPN and the microbarograph when heat was being dissipated in heater No. 2

G 8972

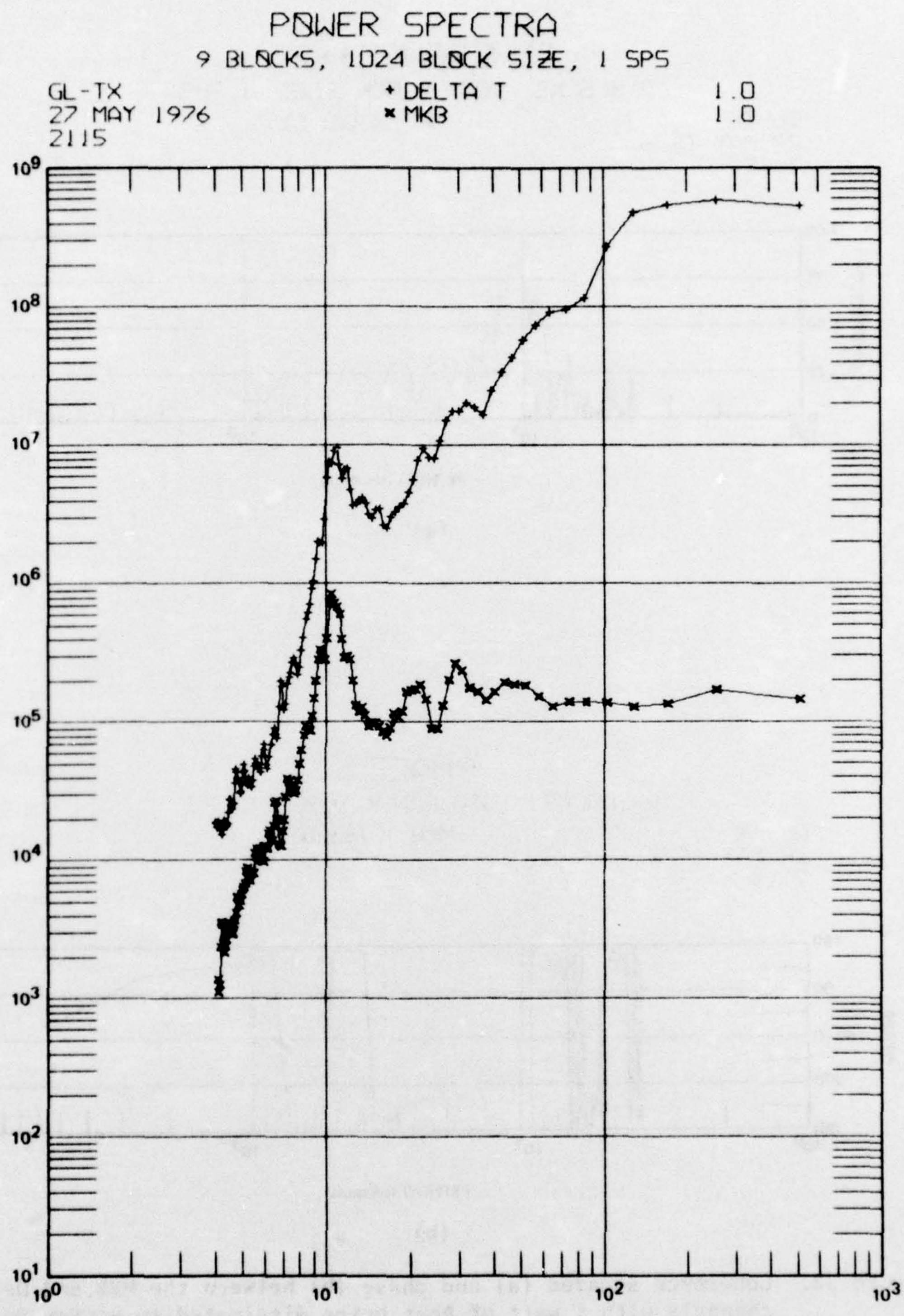
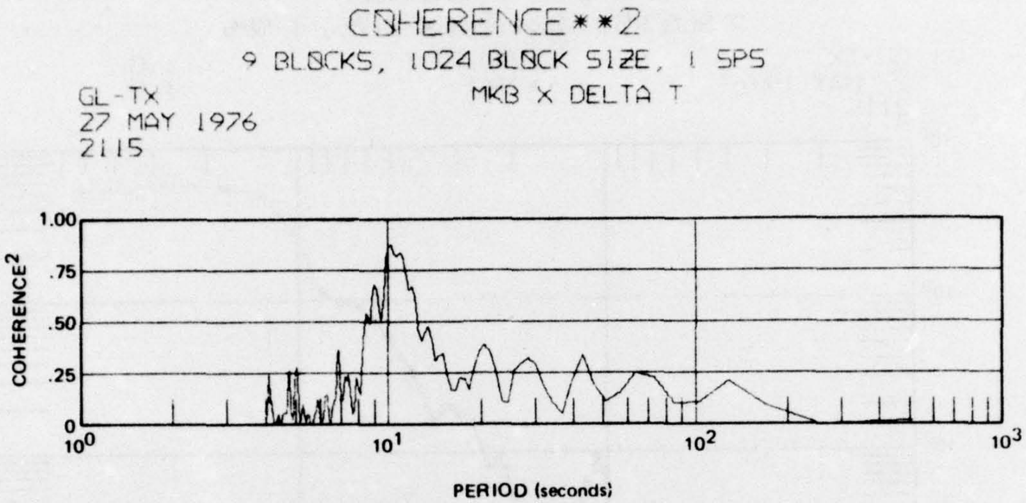
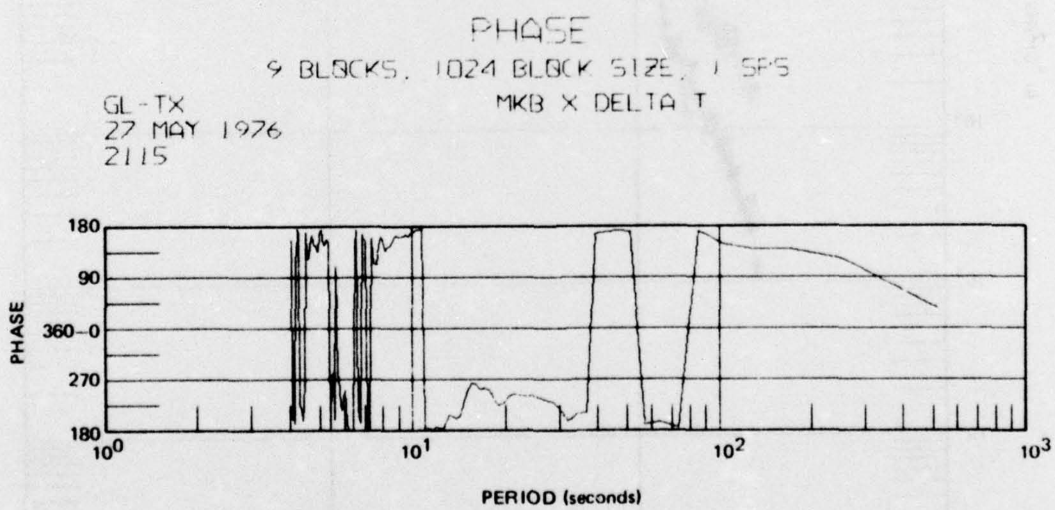


Figure 31. Power spectra of thermal noise as sensed by the Delta T channel and pressure noise as sensed by the microbarograph channel with 1 watt of heat being dissipated in heater No. 2

G 8973



(a)



(b)

Figure 32. Coherence squared (a) and phase (b) between the MKB and Delta T channels with 1 watt of heat being dissipated in heater No. 2

G 8974

To test the theory, the borehole was evacuated to about 14 in. Hg and backfilled with helium. The borehole atmosphere was thus 40 to 50 percent helium. Data were then observed to determine if there was any difference in duration or severity of the upper borehole convection discussed in paragraph 4.4.2 above.The data indicated no apparent improvement. Heating tests with the insulated hole-lock were also repeated with the helium atmosphere. The rapid onset of noise as seen in figure 27 was repeated, required 40 minutes to start as with the air, and there were no obvious differences in level or period in the disturbance detected by the microbarograph or the KS. In the case of convections in the upper borehole, the improvement in threshold gradient is insignificant in comparison with the 15°C diurnal variation. For the heating test, also, the difference between the critical gradients in the 7 cm diameter area for air (0.97°C/m from table 1) and air-helium (3.60°C/m) is probably not sufficient to overcome the ≈ 10°C rise over ambient caused by the resistive heater. In this case, pure helium could provide a significant improvement; however, achieving and maintaining such a high concentration of helium is probably impractical in the borehole.

4.4.5 Effects of Water on Borehole Convection

During a somewhat cool and rainy period from 12 to 20 April, the KS system became very noisy with continuous high-level horizontal noise two to three times higher than the highest levels due to cultural activity. Because the data were virtually useless, the KS was pulled in order to determine whether there was malfunction in the electronic section. When the system was removed from the borehole, an unusual amount of water was found on the cable, upper casing walls, and on the insulating plug at the top of the KS package. It was discovered that the Bowen line wiper was collecting rain water on its top which was leaking through the rubber seals of the wiper. Subsequently, the hole was left open to allow the upper portion to dry and noise tests were run on the KS electronics. When no failure could be found, the KS was installed routinely. The rubber parts of the line wiper were generously greased to prevent leaks and later time constant checks showed a much improved seal. After a normal setting time, the KS operated normally.

No further testing was done on this problem due to the need to proceed with other planned tests. It is not known how water causes the very high noise levels on the KS instrument, but implications are that humidity in the borehole should be kept as low as possible. The problem may well be effectively solved due to the requirement that the borehole must be sealed to prevent pressure effects on the KS package. However, water could prove to be a serious problem in air-filled boreholes and further tests may be required.

5. SUMMARY OF CONCLUSIONS

Work under this program has lead to several conclusions concerning "convection" noise which are summarized below:

a. Noise appearing on horizontal data traces of the Model 36000 System which does not involve vertical data is due to tilting of the seismometer package, whatever the source. Because there are many potential sources of such noise, the arbitrary use of the term "convection" noise is misleading and should be avoided.

b. The KS horizontal seismographs installed at 60 m depth in the Austin chalk at GL-TX respond to tilts caused by atmospheric loading as predicted by theory.

c. The KS horizontal seismographs at GL-TX respond to tilts caused by heavy truck traffic within a radius of 125 m from the borehole in accordance with theory. In addition, measurable vertical displacements resulting from truck traffic were identified. Relatively large tilt noise was identified resulting from passage of trains 300 + m distance.

d. The Model 36000 System responds to pressure acting on its case by tilting. The transfer function between applied pressure and resulting displacement varies when the KS position is changed, resulting in various combinations of phase and amplitude on horizontal traces. This could arise from bending of the casing due to cement assymetries or from the fact that the KS may not seat itself in the holelock in exactly the same position each time.

e. At the greatest pressure sensitivity measured, the Model 36000 will not measurably respond to normally-occurring pressure noise in a sealed borehole. Therefore, "convection" noise is not due to pressures acting on the instrument. However, sensitivity is adequate to record noise on horizontal seismograms due to normal external air pressures if the wellhead is not properly sealed.

f. Low-level pressure noise in a sealed borehole is the same at all points in the borehole within the limits of the instrumentation used. Therefore, calculations concerning pressure noise on the KS may be based on pressure measurements at the top of the hole.

g. Thermistor devices used during this program do not have adequate resolution to detect the naturally occurring minute air temperature changes in or near the seismic data passband which could result in "convention" noise. Such devices may have adequate sensitivity to detect the actual temperature changes in mechanical support parts which are thought to be the result of convections and which give rise to "convection" noise in the KS.

h. The KS instrument is predictably sensitive to changes in temperature at its support points, and is most sensitive to changes in the holelock and/or base of the instrument.

i. Convection activity resulting from inverse thermal gradients at the wellhead causes significant pressure noise in a sealed borehole, but not of sufficient magnitude to cause pressure-induced tilts in the KS. Such convection activity can be controlled by completely filling all voids in the upper 3 m of the borehole with insulating material.

j. When wellhead convections are eliminated, low-level pressure noise continues to be detected by the microbarograph which may be due to convection activity at any point in the borehole. If such convection activity occurs near the mechanical supports of the KS, it is likely that the moving air will result in thermally induced noise on the KS horizontals.

k. Convection cells as observed by thermistors and microbarographs can be generated by artificially causing an adequate thermal gradient. When the hole diameter is large (18 cm), the artificial convection cells apparently diffuse randomly and therefore are not sufficiently organized to produce significant pressure and temperature changes. However, with small diameters (7 cm), convection cells are forced to be relatively organized and, therefore, give rise to coherent pressure and temperature changes.

l. Artificial convection cells, whether or not they are sufficiently organized to generate coherent pressure and temperature noise, can cause tilt noise on horizontal KS seismographs. Since there is no apparent linear relationship between KS noise and thermal convection signals (or pressure signals arising due to them), the KS apparently responds to convections in a random fashion as the disorganized cells alternately cause minute temperature changes in the mechanical supports of the system.

m. Substitution of helium for 40 to 50 percent of the air in the borehole has no obvious effect on artificially induced convection.

6. RECOMMENDATIONS

As a result of this work, the following recommendations are made concerning installation and operation of the Model 36000 Borehole Seismometer System.

a. To avoid measurable effects of cultural noise, the borehole should be located at least 500 m away from heavy truck activity and at least 3 km away from railroads.

b. Boreholes must be provided with wellhead seals to prevent external air pressure noise on KS channels and to prevent introduction of water into the borehole.

c. The upper 3 m of all boreholes should be completely filled with insulation to prevent diurnal convection activity.

d. Because temperature changes (which may or may not be due to convection activity) result in tilt noise on the KS horizontal channels, those parts found susceptible to thermal noise should be protected by insulation. Specifically recommended is:

(1) Installation of an insulating plug directly below the holelock;

(2) Application of insulating material to the base cone of the KS or to the holelock to prevent or minimize temperature changes in the very small contact area ($\approx 20 \text{ mm}^2$) between the KS and the three steel balls. Paraffin, grease, or other material which will not interfere with seating may be adequate;

(3) Continuation of insulating techniques presently being used on the KS package on the stabilizer assembly.

(4) Consider substitution of low-expansion Invar for the steel of the seismometer base and/or the holelock if the above methods prove ineffective.

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